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SCHOOL OF ELECTRICAL ENGINEERING
Department of electrical engineering and automation, Lighting unit

LIGHTING RETROFITTING:

IMPROVING ENERGY EFFICIENCY AND LIGHTING QUALITY

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Abstract

In order to minimize energy consumption for lighting and increasing lighting quality in existing offices old lighting systems can be retrofitted with more efficient luminaires. Additional savings can be achieved by installing a lighting control system. Installation time and costs can be reduced by installing LED luminaires equipped with inbuilt lighting controls. In the case study six rooms were analyzed: in two rooms the old lighting system has been retrofitted with LED luminaires with inbuilt active dimming controls; in two rooms LED luminaires without dimming were installed and two rooms were left as reference. Old and new lighting systems performances were measured in terms of energy efficiency, lighting quality and user satisfaction. The conducted analysis can be used as a monitoring guideline for the evaluation of lighting retrofitting results.

Keywords: efficient lights, lighting quality, user satisfaction, retrofit, Dialux, LENI

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When I arrived at Aalto University six month ago autumn was at its start and the darkness of Finnish winter arrived soon after. However what I will remember about this experience is the warmth and illuminating atmosphere of Aalto Lighting Unit. Now that spring is here it´s time to go out again, it´s time for goodbyes.

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Otaniemi, 16 March 2015

Marta Gavioli

Contents

List of Abbreviations and Symbols

Symbols

Φ	Luminous flux [lm]
η	Luminous efficacy [lm/W]
r_r	Real Discounting Rate [%]
r_n	Nominal Discounting Rate [%]
i	Inflation Rate [%]
η	Luminous efficacy [lm/W]
L	Luminance in the direction of the eye [cd/m2]
$L\delta$	Background luminance [cd/m2]
C	Luminance contrast [-]
Ω	Cut-off angle of a luminaire relative to the eye of an observer [sr]
P	Guth factor [-]

Abbreviations

AS	Annual Savings
CCT	Correlated Colour Temperature
CEN	European Committee of Standardization
CIE	International Commission on Illuminations
CRI	Colour Rendering Index
EU27	European Union considering the state members before 2013
FL	Fluorescent Lamp
FSI	Full-spectrum index
LED	Light-emitting Diode
LCC	Life Cycle Cost
OC	Operating Cost
PC	Investment Cost
RVP	Relative Visual Performance
SPD	Spectral Power Distribution
UGR	Unified Glare Rating

1 . Introduction

The White Rabbit put on his spectacles.
`Where shall I begin, please your Majesty?' he asked.
`Begin at the beginning,' the King said gravely,
`and go on till you come to the end: then stop.'

(Lewis Carroll, Alice in Wonderland, 1865)

1.1 Background

Retrofit is the act of furnishing a systems with new or modified parts or equipment not available or considered necessary at the time of manufacture (1). From the building point of view, retrofitting refers to "work necessary to upgrade an aged or deteriorated building to meet new requirement" (2). Nowadays the aim of building retrofitting is mainly to meet efficiency standards and realize significant energy savings. Indeed the building sector is responsible of 40% of energy consumption and 36% of CO2 emissions in the EU. Since the energy savings and emissions reduction achievable by improving the energy efficiency of buildings are massive, the European Union issued many legislations that aim directly to reduce the energy consumption of the building sector. Moreover about 35% of the EU's building stock is more than 50 years old while the amount of new useful floor space is increasing only around 1% per year. Clearly most of the energy savings potential lies in retrofitting and purchasing new technologies for the existing building stock. As electric lighting is one of the major consumers of electricity in buildings, retrofitting the lighting systems is one of the first options to reach European efficiency goals. Moreover lighting systems are easy to access if compared to others, for example the heating system, and life of the lighting system is much shorter than life of the building, so the retrofitting potential is important: about 75 % of European lighting installations are estimated to be older than 25 years and thus to be updated. Finally there are already more efficient technologies on the market that are not yet so commonly implemented. Efforts to reduce energy consumption in the lighting sector have been on one hand imposed through regulation, standards and directives and, on the other hand, realized by appropriate lighting design strategies.

However energy savings are not the only requirement for a new lighting system, any attempt to develop an energy efficient lighting strategy should have as first priority to guarantee that the quality of the luminous environment is as high as possible.(3) In the case of lighting in workplaces improving lighting quality is particularly convenient since it can improve productivity. Lighting can impact work performance mainly in three ways: affecting the visual system, affecting the circadian system and affecting mood and motivation (4). The ways in which lighting influence visual performance and the ways to avoid visual discomfort have been subjects of lighting researches for years and they are now well understood even if not always applied. On the contrary impacts of lighting on the health, wealth and safety of people still need to be studied more, as well as the ways lighting operates on mood, on motivation and behaviour. (5)

Lighting retrofits can provide a flexible, maintainable long-term system in any type of building if properly planned. A general planning procedure can be followed to realize a successful lighting retrofitting in terms of better light quality, improving working conditions, achieving energy savings and benefitting occupants as a whole. If retrofitting approaches have a general validity, the technologies that provide the foundation for these strategies improve every year and change over time. Nowadays there is a wide range of lighting retrofitting technologies on market that offer improvements in lamp, ballast, luminaire technology (T5 or LEDs) and lighting control. There are many means to control lighting systems, for instance manual dimming, daylight harvesting and switch-off based on occupancy sensors. The implementation of new and more efficient light sources, task-ambient lighting and the use of lighting controls lead to significant energy savings, as widely described and quantified in literature (6). If accurately designed, the energy savings due to the control system can be even higher than the savings achieved by using efficient light sources. However in retrofitting an old lighting system the installations time and costs increase if additional wiring is needed for the control. To achieve maximum saving all the factors that influence the investment cost should be taken into account and those depends on the particular case Therefore lighting retrofit projects should be accurately designed in order to achieve the maximum savings.

1.2 Objectives

The main objectives of this case study were to monitor the retrofitting project and to quantify the energy savings achieved thanks to the installation of the new lighting source technology equipped with inbuilt control systems. Six rooms have been studied: in two of them new LED luminaires with active dimming were installed. In similar two rooms new LED luminaires without dimming were installed. Two other rooms were left as reference rooms. Two different analyses have been carried out. The first analysis deals with the comparison between pre and post retrofit conditions in each room. The second analysis compares the two different post retrofit conditions: new luminaires with or without inbuilt active dimming controls. The effects of the lighting retrofit are analysed in terms of energy consumption, lighting quality, user satisfaction and economical savings. The analysis are based on photometric and electrical measurements, software simulations and users surveys.

1.3 Outline of the thesis

This thesis can be divided into two parts: the first three chapter deals with the background of lighting retrofitting and the second part describe the case study.

- Chapter 2 presents data about energy consumption in lighting, lighting demand evolution, offices lighting retrofitting potentials in Europe and European regulation on energy efficiency in lighting.
- Chapter 3 analyses the influences of lighting on work performance and define aspects of lighting quality in offices.
- Chapter 4 introduces lighting retrofitting practice and common lighting retrofitting technologies nowadays on the market
- After the theory part, the case study is introduced: Chapter 5 describes the retrofitting project as well as the methods used to collect data and methods used to perform the analysis.
- In Chapter 6 analyses results are presented.
- Finally, the thesis concludes verifying how well the aim of the work has been reached and suggests further monitoring possibilities.

2 . Lighting energy consumption

Customers don't want kilowatt-hours; they want services such as hot showers, cold beer, lit rooms, and spinning shafts, which can come more cheaply from using less electricity more efficiently. (LOVINS, the Negawatt Revolution, 1990)

2.1 Electricity demand

Artificial lighting nowadays is mostly powered by electricity. Because of the versatile nature of its production as well as its consumption, electricity is becoming more and more the favourite form of energy, hence the electricity demand is increasing at a faster rate than the global energy demand. In the last decades the global consumption growth rate of electricity has been 3% while the overall primary energy demand growth rate has been 1.9% (3). In 2008 total world energy supply was 143 851 TWh, while end use was 98 022 TWh. Electricity accounted for the 17.3% of the end use energy demand (17250 TWh) (7). Moreover the electricity sector is the largest source of greenhouse gas emissions, accounting for 11.4 gigatonnes of equivalent CO2, about 31% of global emissions (36.7 Gt). There is a considerable technical potential for energy efficiency improvements along the entire energy value chain: from extraction of primary energy resources to their transformation into electricity, transportation and distribution of energy, and ultimately to the final use by equipment and devices.

2.2 Electricity consumption in lighting

One of the biggest electricity end use is lighting, globally it is estimated to consume about 2 650 TWh of energy annually, which is almost 19% of global electricity consumption (8). In the industrialized countries, national electricity consumption for lighting ranges from 5% to 15% of the total electricity usage. On the other hand, in developing countries the value can be even higher than 80%. Most of the lighting electricity is used in the tertiary sector, as shown in Figure 1 . Being a great electricity consumer means also being responsible of a great amount of greenhouse gas emissions, the lighting sector is responsible for almost 1 900 mega tonnes per year.

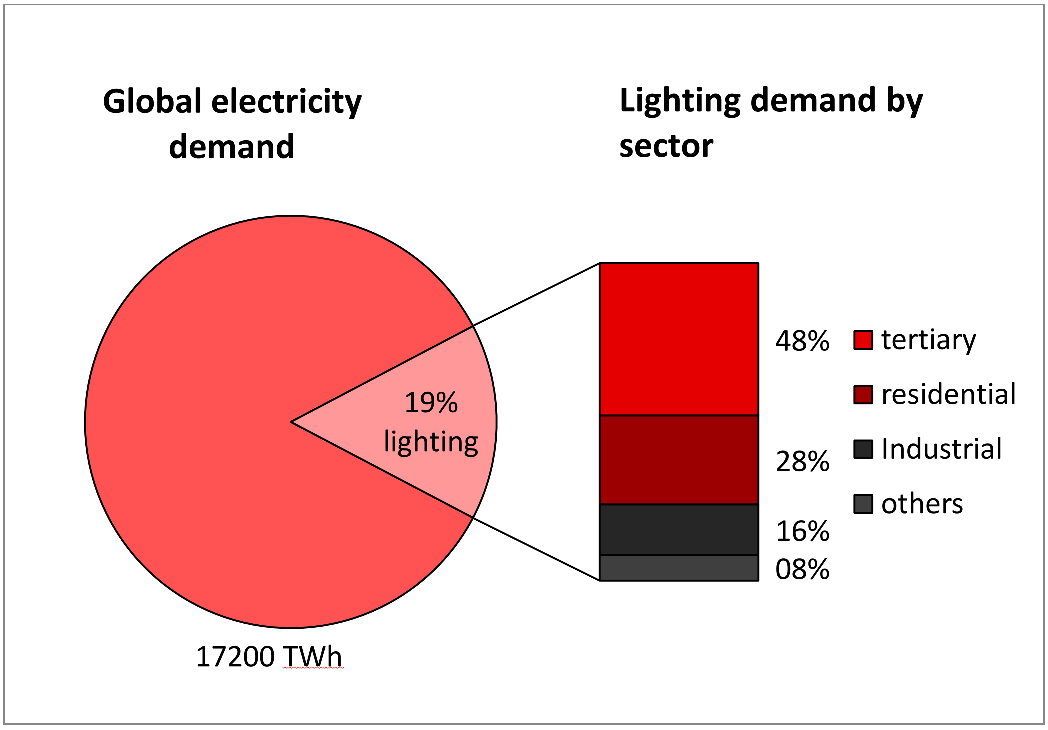

Figure 1 *– Lighting electricity consumption by sector: indoor illumination of tertiary-sector buildings uses the largest proportion of electricity (derived from* (8) *data and analysis).*

2.3 Lighting demand evolution

Until the latter part of the nineteenth century artificial light was an expensive utility: its average price was 13000 € per Mlmh and light mainly came from tallow candles.(9) Artificial light has started to be used in great quantity only when the modern lamps appeared. Currently artificial light usages surpass the most exaggerated dreams of two hundred years ago, more than 33 billion lamps operate worldwide (8) and lighting engineering and technologies have been developed till the point that light can be directed, diffused and altered in colour as desired. Figure shows how in the span of 200 years total lighting consumption increased from less than 20 giga lumen-hours in 1800 to 10,000 Glmh in 1900 to nearly 800,000 Glmh in 2000 (9).

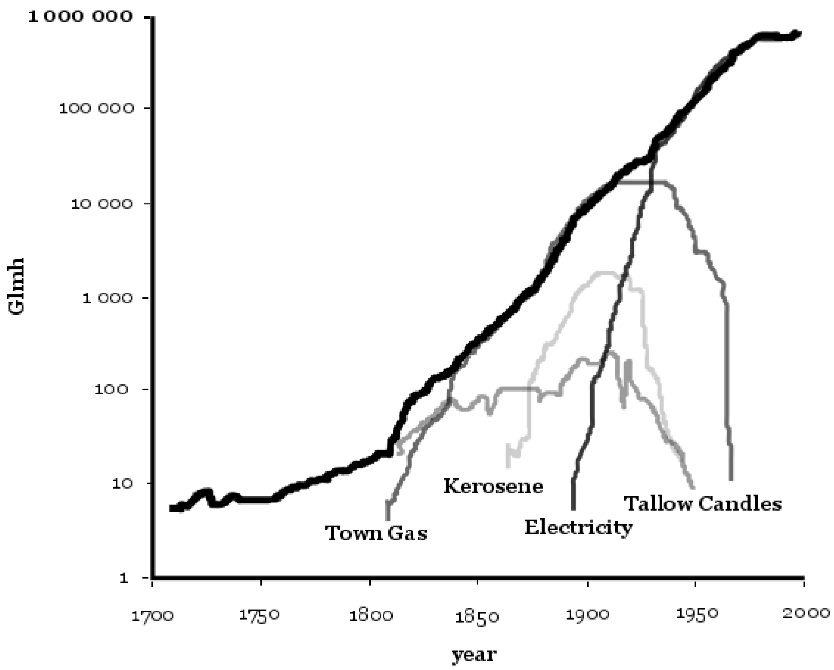

Figure 2 - *Global Consumption of Lighting by Source* (9)

Per capita consumption has increased by a factor of 8400, from a 5 kilolumen-hours at the beginning of the 19th century to 42 megalumen-hours today (8). Over the last decade, global demand for artificial light grew at an average rate of 2.4% per annum. With an average cost of almost 2.50€ per Mlmh, electric lighting is clearly no more a luxury. From these analyses it is clear that the major influence on the consumption of artificial light is its affordability – the cheaper it becomes and the wealthier we are, the more we use it. But lighting demand is very elastic: per capita consumption in the last two centuries grew much more than variations in per capita income and lighting price (9). With current economic and energy-efficiency trends, it is projected that global demand for artificial lighting will be 80% higher by 2030.(8)

2.4 The building sector

The construction of buildings and their operation account for 2973 Mtoe, that is more than one third of primary global energy demand and is the biggest energy consumer among the three energy-using sectors: transportation, industry and buildings (Figure 3). With current policies, due to the increasing of population, economic growth, higher living standards and greater use of electric appliances, energy consumption in building is supposed to grow 1% every year, reaching 3870 Mtoe by 2040 (10).

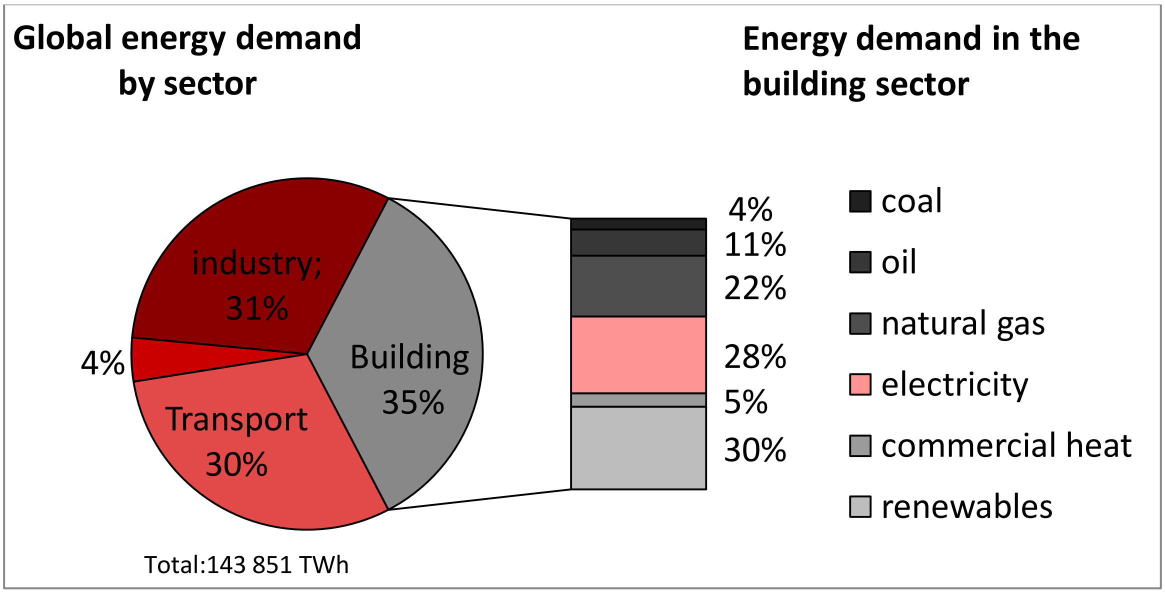

Figure 3 *- Final energy consumption by sector and buildings energy mix, IEA 2010*

In the territories of EU27, Switzerland and Norway, it is estimated that there are $25*10^9$ m^2 of useful floor space.(11) Office buildings comprise the second biggest portion of the non-residential stock category with a floor space corresponding to one quarter of the total non-residential floor space. In non-residential building sector most of the energy is consumed for the operation of existing structures since the construction of new building is rare: the useful floor is increasing at a rate that is only around 1% per year. At the same time most buildings have long life spans, meaning that more than half of the current global building stock will still be standing in 2050. In the OECD countries, this will be closer to three-quarters. Buildings are much more frequently refurbished than replaced. Due to the low retirement rate of buildings combined with relatively modest growth, most of the energy and CO2 savings potential lies in retrofitting and purchasing new technologies for the existing building stock.

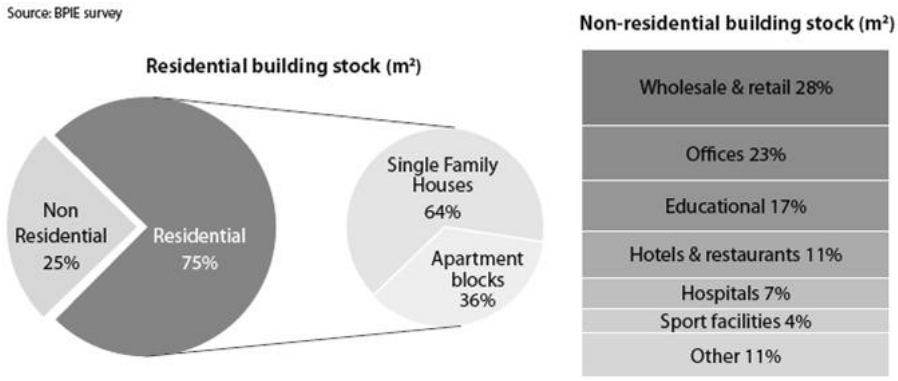

***Figure 4** – EU27, Swiss and Norwegian buildings stock*

Lighting is responsible of 18% (1750 TWh) of the total electricity consumption in the whole building sector (10) while in office buildings lighting is globally the leading energy consumer accounting from 30% to 40% of the total energy consumption (11). Moreover lighting demand growth in the building sector is far from being saturated and with current policies electricity consumption for lighting in 2040 is supposed to be 3025 TWh. On the other hand lighting is believed to be one application where electricity demand growth might be considerably reduced. This is because lighting installations have relatively short lives compared to building, are easy to access and there are already existing energy efficient technologies that are not widely used (4). For example in the commercial sector the replacement of old linear fluorescent lamps by more efficient type of light sources with active control can cut energy consumption by 25%. (10)

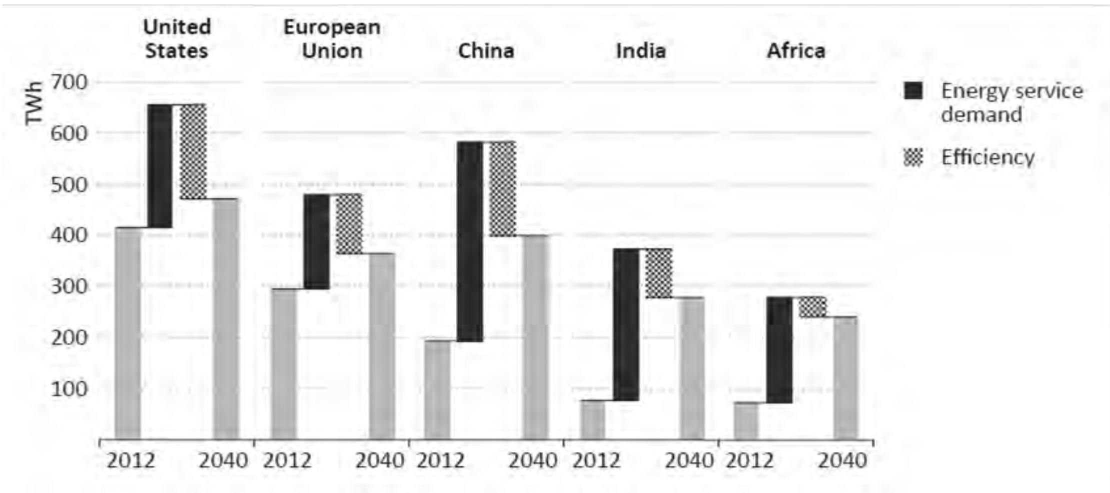

***Figure 5** – Growth of electricity demand for lighting in building: savings potential* (10)

2.5 Reducing energy consumption in lighting

Attempts have been made to reduce lighting electricity consumption through regulations and design strategies.

Regulations

For many years the aim of the lighting regulations was to assure the users' health and safety, in other words regulations used to state the minimum light level needed to accomplish a certain task in the safest way possible, minimizing accidents and avoiding damage to the visual system of the user. Nevertheless in the last decades also limiting the growth of energy demand has become a key element in the lighting policies. To achieve this point two approaches are mainly used: limit the power lighting density and ban the energy-inefficient technologies (4).

An example of banning inefficient equipment can be found in EcoDesign European directive and its implementations (12). With this directive the EU defined a series of measures for the economical and sustainable use of resources. After prohibiting less efficient conventional ballasts for fluorescent lamp in 2000(13), reducing hazardous materials content (14) and regulating the disposal of discarded electronic devices in 2003 (15), the EU issued the EcoDesign framework directive (16), to define requirements for acceptable environmental design (eco-design) of energy-using products. In November 2009, this directive was replaced with an updated framework directive (12), relating to the eco-design of many energy-related products and containing measures also for tertiary sector lighting products. This directive reflects European climate targets set at the beginning of 2007 that extend to 2020. The core objective of these ambitious goals is to reduce CO2 emissions in the EU by 20% by 2020.

In the non-residential lighting sector, reductions of just over 20 million metric tons of CO2 are being targeted and another 24 million metric tons in residential lighting. The impact on light sources is the focus of this measure, realized by setting quality criteria (functionality requirements) for directional lamps, light emitting diodes lamps and related equipment (e.g. halogen lamp control gear, LED lamp control gear, control devices and luminaires). When the first stage entered into force on 1st September 2009 the changes were difficult to see for non-experts, because the main effect was the transition from less efficient towards more efficient types within the same technology. The only technology change has been in stage two (1st September 2014) when all the incandescent types have been phased-out. As of stage three in 2016, energy efficiency index EEI of LED directional lamps and modules will need to be less than 0,20; meaning that LED lamp have to meet energy efficiency class A.

From stage one 2013 onwards functional requirements valid for both LED directional and non-directional lamps have been set. These requirements typically relate to lamp survival rate and lumens maintenance, switching cycles, starting and warm up times, premature failure rates, colour rendering and consistency, power factor. Requirements prescribe also when a LED lamp can be labelled as suitable to be retrofit to existing lamp types. Regarding control gears the regulation does not state any efficiency requirements but there are compatibility requirements with A class or better lamps.

An example for regulation that addresses directly the purpose behind of the policy (the reduction of electricity consumption) is the EN 15193 (17). This European standard aims to establish conventions and procedures to estimate the lighting energy needed in buildings. It presents two methods: the calculated method and the metered method. After giving a methodology to compute the energy required by the lighting system, this standard defines a numeric indicator of energy performance of buildings. LENI (lighting energy numeric indicator) quantifies the amount of energy that is used by a lighting system per square meter per year. The standard gives also benchmark LENI values limiting the energy used by the lighting system. En 15193 procedure to compute energy consumption has been used in the analysis of the case study so a complete description and example of application of this standard can be found in Chapter 5.3.1

Design

To actually limit the energy consumption it is necessary to choose the right design approach and the right technology. Currently there are three main trends in the design approach (4). The first one is not to maintain the recommended light level everywhere but only on the task area, illuminating less the surrounding zone. In this way the energy consumption of the installation would be lower than when a uniform lighting is used. The second is to take advantage of daylight that, in addition to reduce energy consumption, is believed to be good for avoiding circadian disruption. The provided amount of daylight is controlled to avoid visual discomfort and overheating, the artificial light is provided with sensor so that it can dim or switch off when daylight is enough. The third trend is the usage of control systems to avoid the use of lighting where nobody is present. The different design approaches are described in details in Chapter 4.2.

3 . Lighting quality in offices

[Lighting quality is...]Like pornography, we know it when we see it but what it is differs from one individual and culture to another.
(R.Boyce: Human Factors in Lighting. 2014)

3.1 Lighting and work

As our world become increasingly service-oriented, more and more people work in offices or workstation environments. In most work environments, productivity and efficiency are high-priority goals but there is also a trend in increasing employee satisfaction in most workplaces.(18) Inevitably, lighting design solutions are expected to support all these requirements, especially because lighting in one of the main factors that can influence human performance. In particular lighting can influence job performance in three ways (4):

- **Affecting the visual system:** Obviously without a proper lighting there isn't any performance since the user is not able to see. Lighting makes the job task visible. Visibility is defined by the user's ability to detect objects or signs of given dimensions, at given distances and with given contrasts with the background (3). Visibility is influenced by: visual size, colour, luminance and position of the observed object; luminance contrasts; colour difference; objects movements; position and quality of the image on the retina; retinal illuminance (4).
- **Affecting the circadian system:** the circadian timing system in humans rules the sleep-wake cycle and many different hormonal production rhythms. The organ that controls these cycles is the suprachiasmatic nucleus that is directly connected to the retina, so the amount of light and its spectrum reaching the retina influence the SCN functions. These physical mechanisms are proven to impact awakens and alertness. (4)
- **Affecting mood and motivation:** how much work is done and of what quality depends on many factors but mostly on the employee mood and motivation. Even motivation is influence by many factors (reward, risk, need, etc.) including the work environment. Lighting is part of the visual environment and it is through the perception of the visual environment that the visual system creates a model of the external world. The interpretation of the external world is

not confined to the simple perception of what is seen but it deals also with the reading, conscious or not, of other messages. This interpretation always gives an emotional response: motivation, satisfaction, pleasantness and so on. From this point of view, lighting can influence the mood both if it is cause of discomfort or not, but the user emotional reaction is mostly subjective and difficult to predict since depends on many factors, for instance culture, situation, social contest.(4)

3.2 Visual tasks, visual performances and visual discomfort

The main impacts of the lighting on the human performance are the one affecting the visual system and they are also the one that have been studied the most. Lighting research for interiors has been focused especially on the topics of visibility and visual comfort. Research result has been the development of a validated model that allows the prediction of the effect of lighting and task conditions on visual performance, and an understanding of the conditions that cause visual discomfort (5). These models are based on the concepts of visual task, visual performance and visual comfort.

Office work requires fulfilling a number of different tasks, for example reading and reviewing paper work, writing, working with video terminals, filing, copying, etc. Task performance is the performance of the whole task. On the other hand visual task is the visual component of the whole task; it is what is requested to the visual system to fulfil that certain activity. In other words visual task is the perception and how quick the visual system perceives the objects with which the user has to work and the immediate surroundings (19).

Visual performance is the performance of the visual task. It is defined by the speed and the accuracy with whom the visual task is fulfilled. Visual performance is then the attitude of the user in reacting when the details of the visual task enter the visual field. Visual performance depends primarily on the visual acuity of the user (accommodation, regulation of the incident light, convergence of the visual axes, ocular motility, colour sense, presence of visual defects, adaptation); on the features of the visual task (visual size, illuminance, texture) and of the visual environment (luminance contrast) (4).

Many methods have been developed to predict the effect of lighting on visual performance. A simple but rigorous approach is the Relative Visual Performance (RVP) Model developed by Rea et al. and the end of the eighties (4). This model shows how the time in completing a visual performance varies in respect to the visual size of the task, adaptation luminance and luminance contrast, defined as:

$$\mathbf{C} = \frac{|\mathbf{L_d} - \mathbf{L_\delta}|}{\mathbf{L_b}} \qquad (3.1)$$

Where:

C= luminance contrast

L_δ= luminance of the background (cd/m^2)

L_d= luminance of the detail (cd/m^2)

The difference between RVP model and many other proposed is that in this case the characteristic of the task are described by quantities that are directly measurable. The visual task used as reference was one that could be directly used as a measure of the speed of the performance. Simply it was the reaction time to the onset of a square stimulus. Measurements were taken for a wide range of luminance contrasts, adaptation luminance and visual size (solid angle subtended by the stimulus on the eye). To have a relative measurement of the reaction speed, reaction times are normalized in respect to the shortest time occurred. Then the inverse of the reaction time was plotted against luminance contrasts, adaptation luminance for different dimensions of the visual size as shown in ***Figure 6***. The adaptation luminance can be expressed as conventional retinal illuminance (1 troland =10000 candelas per square meter). The shape of this model has been described as the plateau and escarpment of visual performance.

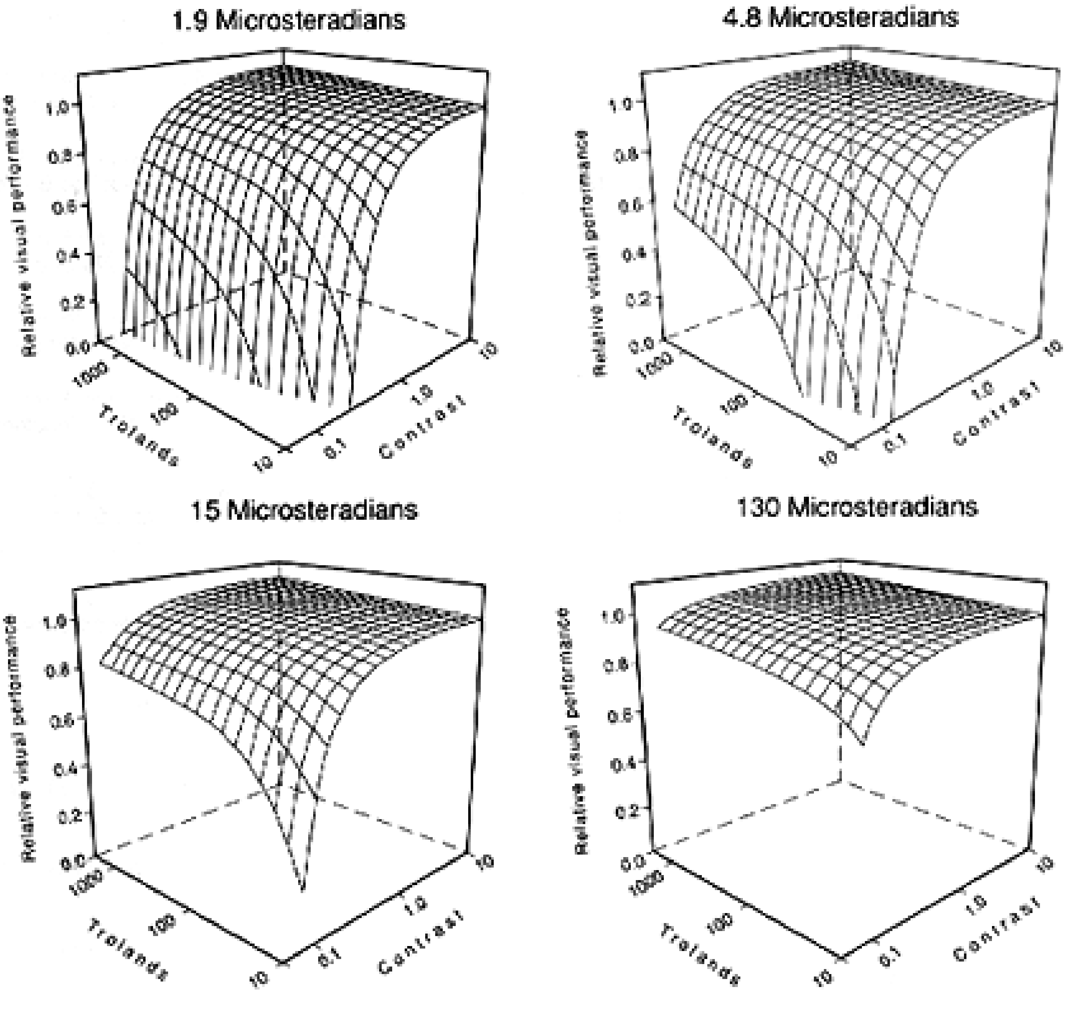

Figure 6 *– Relative Visual Performance (RVP) plotted as a function of luminance contrast and adaptation luminance for different target sizes measured in solid angle* (4)

From this graph it is evident that luminance contrast is the major determinant in the fulfilment of the task. For a wide range of luminance contrast there is very little difference in reaction speeds but when contrast fall under 0.4 the performance decrease really fast and in one non-linear manner. In addition, for the same contrast value the reaction speed is higher with higher luminance levels and performance tends to saturate at lower luminance contrast. So, in general, visual performance is improved with increasing luminance level. Yet, there is a plateau above which further increases in luminance do not lead to improvements in visual performance. Thus increasing luminance levels above the optimum for visual performance may not be justified and can on the contrary lead to excessive use of energy. RPV model represent the most complete and accurate method to predict the effect of task and lighting variables on the visual performance. Since all the variables to take into account can be directly measured this method is simple to use and its predictions have been independently validated (5).

Lighting in offices is mostly intended to permit the extraction of information from the visual environment.(4) If lighting doesn't allow this process visual discomfort occurs. This happens if it is difficult to reach a high level of visual performance, if the visual environment presents too little or too much information, if lighting creates distraction from the task, drawing attention to other objects. The concept of comfort is not directly measurable since if a situation is comfortable or not is a subjective matter closely linked to users' past experiences, expectations and sensibility. Nevertheless conditions that generally cause discomfort feel can be identify. In particular, aspects that can cause visual discomfort are insufficient light to perform the task (visual performance depends also on luminance contrasts and adaptation luminance, if these are not sufficient users will have difficulties to perform the visual task), uniformity, glare, veil reflections, shadows, flickers. Whether or not these aspects create visual discomfort depends very much on the contest as the same visual conditions may be considered uncomfortable in one situation but attractive in another, for examples flickers in an office or in a disco. The conditions that cause discomfort are well known so these phenomena can be produced or eliminated as desired by the designer.

3.2.1 Uniformity of the work surface

Uniformity is generally described as the ratio between highest- and lowest-illuminance values in the given room or space. Uniformity is described in terms of illuminance even if visual perception depends on the luminance of surfaces because general practice is to use surface with similar reflectance within the task area. Acceptable reflectance values are also provided in many lighting standards. For example, the European standard EN-12464-1 (20) proposes the following reflectance factors for the main room surfaces:

- Ceiling: 60-90%
- Walls: 30-80%

- Floor: 10-50%
- Work surface: 20-60%

A complete uniform visual field is undesirable since it is perceived as not interesting and not stimulating, but also too much not-uniformity is undesirable since it creates distraction (3). Studies about people reactions to various lighting patterns shown that the preferred lighting form is having a uniform illuminance over an area of about 1m^2 where the task has to be accomplished and less illuminance in the surrounding area if the task deals with 2-D work. If the objects to work with present 3D surfaces (industry works, prototypes) then less uniformity is needed in order to perceive shape and texture of the object. (4) In workspaces with video screens the luminance of the display should be also taken into account when planning the lighting in order to provide such level of illumination that does not create abrupt changes in luminance between screen and the rest of the room.

3.2.2 Glare

Glare is the sensation produced by luminance within the visual field that is sufficiently greater than the luminance to which the eyes are adapted to cause annoyance, discomfort or loss in visual performance and visibility. (21) If the high luminance comes from the direct presence of a light source within the visual field the glare is said direct. Direct glare, minimization or avoidance is possible by mounting luminaires well above the line of vision or field of vision or by limit both brightness and light flux in the common field of view. On the other hand, reflected glare is due to bright reflections from polished or glossy surfaces. It can be avoided by appropriate choice of interiors. Distinctions between different types of glare can be also made taking into account the reaction that glare induces in people. From this point of view up to 8 types of glare have been identified (4) but the most common in indoor workspaces are two: disability glare (physiological glare) and discomfort glare (psychological glare). Disability glare is the effect of stray light in the eye that causes reduction in visibility and visual performance. When disability glare is present, occupants usually notice an immediate reduction in their ability to see or to perform a visual task. They might react by shifting their position or using shading devices, such as closing blinds or curtains. Discomfort glare is glare that produces discomfort. It does not necessarily interfere with visual performance or visibility. However, they might experience certain physiological symptoms such as headaches. Disability glare and the physical mechanism that produces it are well understood, it has an effect of visual capabilities that can be easily measured with psychophysical procedures. Disability glare is then easy to detect and to avoid. On the other hand there is not yet a complete physical explanation of discomfort glare, it is said to occur when people complain about visual discomfort due to the presence of bright sources.(4) there are many methods to measure the probability of psychological glare, in Europe it is used the so-called UGR (Unified Glare Rating) method defined by International Commission on Illuminations (CIE). UGR calculations involve the luminance and size of the glare source, the luminance of the background and the position of the glare source relative to the line of sight. UGR is defined as:

$$\mathbf{UGR = 8log\left[\frac{0{,}25}{L_\delta}\sum\frac{L^2\Omega}{p^2}\right]} \tag{3.2}$$

Where:

- L=luminance of lighting parts of every luminaire in the direction of the eye (in candelas per square meter).
- Ω=cut-off angle of a luminaire relative to the eye of an observer (in sr)
- P=Guth factor of spatial position of every single luminaire relative to the field of view
- Lδ=background illuminance (in candelas per square meter).

The higher is the luminance of the glare source and the larger its size, the greater will be the level of discomfort glare. Conversely, the higher the luminance of the background and the further the glare source is from the line of sight, the lower will be the level of discomfort glare.

UGR is the result of many years of study by the CIE and represents the state of the art in glare prediction methods. However, there is doubt about how well it deals with LED luminaires, which contain multiple small points of high luminous intensity; with daylight, since glare from daylight appears to be tolerated more than predicted if there is a pleasant view from the window and for integrated systems that combine day lighting and electric lighting (22).

The EN 12464 specifies the UGR limits for activities and visual. To prevent glare and respect the standard limits best practice suggest to use large luminaires with low luminance, luminaires with butterfly-shaped curve of luminous density (maximum luminosity in the angled parts of the curve) and surface finishes that diffuse and scatter light instead of glossy ones that create strong reflections. Moreover light sources should be covered or partially obstructed so that it is not directly visible in a 65-degree angle and windows should be covered by protective shutters. Attention has to be paid to match luminaires to workstation and avoid reflections. Glare from windows usually arises when direct sunlight enters the room creating both direct and reflected glare. Alternatively sunlight reflections off exterior surfaces, for example the glazed facade of neighbouring building or by the direct view of the sky, may result in high window luminance causing glare. Work areas using screen with high-gloss finish might need an individual approach: separate window shutters or even a specific setting of a lighting system. (23).

3.2.3 Correlated colour temperature

In CIE International Lighting Vocabulary the correlated colour temperature (CCT) is defined as: "the temperature of the Planckian radiator whose perceived colour most closely resembles that of a given stimulus at the same brightness and under specified viewing conditions". In fact the spectral power distribution (SPD) of an ideal blackbody radiator depends on the temperature of the body: the warmer the body is the bluer is the emitted light. Planckian radiator SPD can be completely determined from its colour temperature in Kelvin (K). Chromaticity of the radiation of Planckian radiators goes from orange/red to white and finally to blue. The locus of points in a chromaticity diagram that represents chromaticity of the radiation of Planckian radiators at different temperatures is called blackbody locus (***Figure 7***). Correlated colour temperature is a measure of light source colour appearance defined by the proximity of the light source's chromaticity coordinates to the blackbody locus, as a single number rather than the two required to specify a chromaticity. The recommended method of calculating the correlated colour temperature of a stimulus is to determine on a chromaticity diagram the temperature corresponding to the point on the Planckian locus that is intersected by the agreed isotemperature line containing the point representing the stimulus.

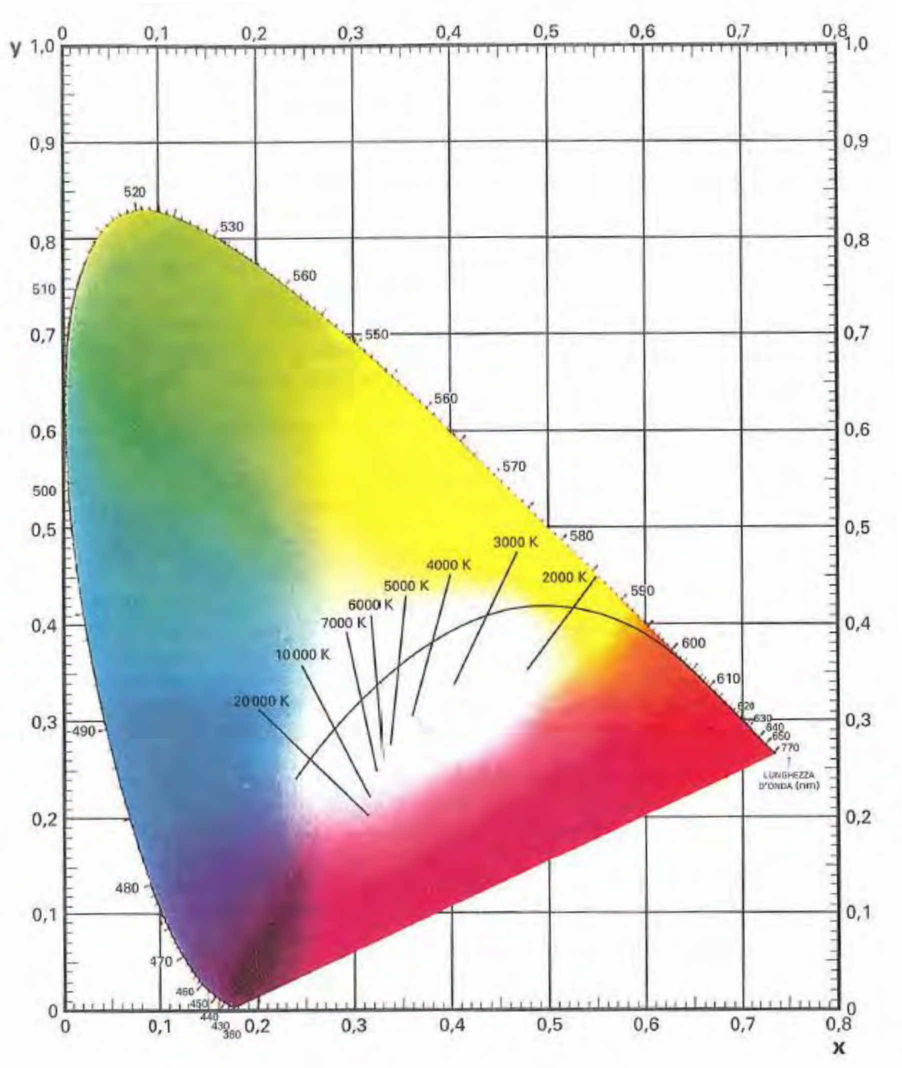

Figure 7 *– CIE 1931 (x, y) chromaticity diagram. The Planckian locus and isotemperature lines are located in the center of the diagram.*

Since it is a single number, CCT is simpler to communicate and it is widely used in the lighting industry to report the colour appearance of "white" light emitted from electric light sources. CCT values of most commercially available light sources usually range from 2700 K to 6500 K. Lamps with low CCT values (2700 K to 3000 K) provide light that appears "warm," while lamps having high CCT values (4000 K to 6500 K) provide light that appears "cool." Practical light sources of different SPD but identical chromaticity will also have identical CCTs but not always the opposite is true. The weakness of CCT is that two light sources with the same CCT can have very different chromaticity and will look very different to the eye. The light emitted by source whose colour coordinates are upon the blackbody locus have a greenish-white appearance, while the light emitted by sources placed under the blackbody locus have a purple-white appearance.

In 1941, Kruithof conducted a study on the colour of lamps for general illumination, the aims of Kruithof's experiment was to set whether the illumination appeared 'pleasing'. Results are displayed in a two dimension diagram where correlated colour temperature (CCT) is reported along the abscissa and illuminance E is reported along the ordinate axis (***Figure 8***). Two curves are drawn on the diagram. They show the limits between which an illumination is considered 'pleasing'.

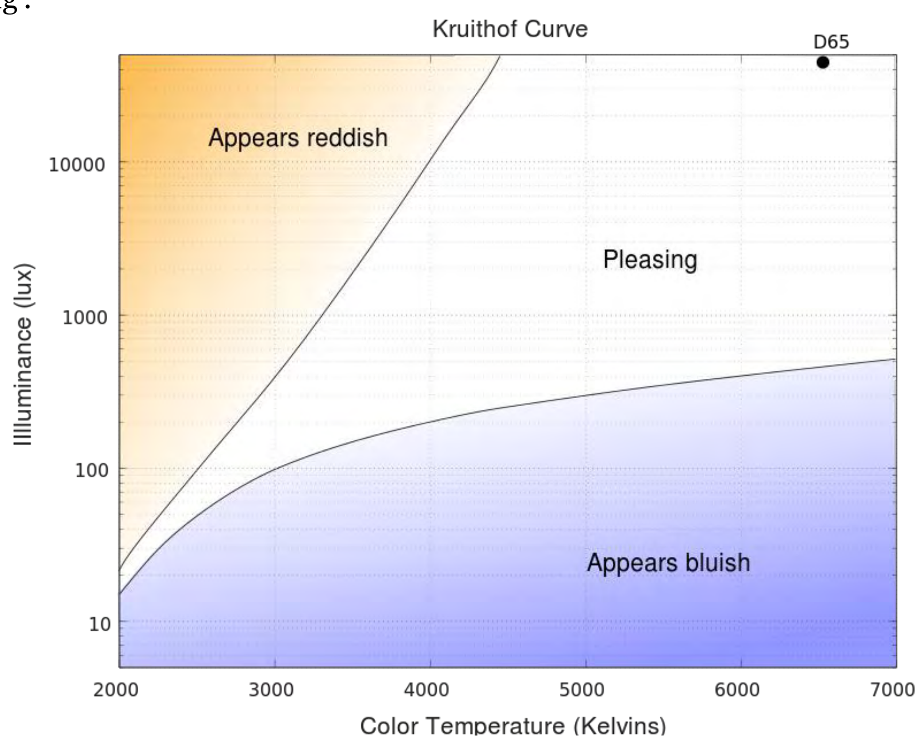

Figure 8 *– Kruithof's diagram.*

The article gives little information on how the diagram was derived. Kruithof himself declared that it was a pilot study based entirely on the observations made by himself and his assistant. Kruithof introduced a variable number of lamps in a room, so that the observer could not guess which type of illumination was on. All lights could be graded in intensity while controlling the correlated colour temperature

(CCT). Beneath 2850 K, he would use incandescent lamps with variable current to produce light sources. For higher CCT, the experiment was conducted with daylight originating from a window or daylight luminescence lamps. For some part of the diagram Kruithof relied on common sense (24). There is little information available about the size and the geometry of the room, on the tasks proposed to the observers, as well as on the number of participants. Moreover at that time fluorescent lamps just appeared and halogens haven't existed yet and Colour Rendering Index has not yet been defined. Nowadays "Kruithof effect" is still on although it is not unanimously accepted and several attempts reassess its scientific accuracy through more rigorous methods have been carried on. Nowadays fluorescent lighting has matured, new lighting technologies have been developed, and individual experience has considerably changed in terms of quality of available sources and management of illumination. While these newer sources can still achieve correlated colour temperatures and illuminance levels that are within the comfortable region of the Kruithof curve, variability in their colour rendering indices may cause these sources to ultimately be displeasing. Moreover there are questions on the interpretation of 'pleasing'. There could be several reasons for which an observer can judge the illumination pleasing. Task performance could be facilitated, colour appearance could contribute to beautification, global subjective impression could improve, and cognitive appreciation could interact with direct sensation. Kruithof's findings may also vary as a function of culture or geographic location. Desirable sources are based on an individual's previous experiences of perceiving colour, and as different regions of the world may have their own lighting standards, each culture would likely have its own acceptable light sources.(4) In conclusion Kruithof curve should be taken into account as a general rule of thumb, considering that several studies have yielded both to similar conclusion and to opposite ones.(25)

3.2.4 Colour Rendering

Colour rendering is a general term for describing the ability of a light source to provide colour information to a human observer when objects are illuminated by that source. The colour rendering properties of a light source cannot be accurately assessed by visual inspection of the light source; rather, a calculation procedure must be used. (22) Many methods for quantifying the colour rendering properties of electric light sources have been proposed. All of these methods have limitations in characterizing the various aspects of colour perception associated with colour rendering. Every method utilizes the SPD of the light source. Most, but not all, incorporate one or more reference light sources to which a particular light source is compared. Most procedures also incorporate a reference set of coloured objects to be illuminated. Most known colour rendering metrics are three: colour rendering index (CRI), full-spectrum index (FSI), and colour gamut area (GA). (26)

Colour Rendering Index (CRI) is currently the only colour rendering metric recognized internationally, and it is universally used by the lighting industry. In general terms, CRI is a measure of a light source's ability to show object colours "realistically" or "naturally" compared to a familiar reference source. CRI is calculated from the differences in the chromaticity of eight CIE standard colour samples when illuminated by a light source and by a reference illuminant of the same correlated colour temperature (CCT); the smaller the average difference in chromaticity, the higher the CRI. A CRI of 100 represents the maximum value. Lower CRI values indicate that some colours may appear unnatural when illuminated by the lamp. For CCTs less than 5000 K, the reference illuminants used in the CRI calculation procedure are the SPDs of blackbody radiators; for CCTs above 5000 K, imaginary SPDs calculated from a mathematical model of daylight are used. These reference sources were selected to approximate incandescent lamps and daylight, respectively. The weakness of CRI is that light sources with different CCT are compared to different reference sources so, technically, CRI's can only be compared for sources that have the same correlated colour temperatures. Moreover CRI was developed to compare continuous spectrum sources who's CRI was above 90 because below 90 it is possible to have two light sources with the same CRI, but which render color very differently.

Full-spectrum index (FSI) is a mathematical measure of how much a light source's spectrum deviates from an equal-energy spectrum. An equal-energy spectrum is an imaginary spectrum that provides the same radiant power at all wavelengths, thus representing a "full" spectrum. Therefore, for humans to see object colours, a light source must generate light from more than one region of the visible spectrum. Subtle differences in the perceived colours of objects arise from slight differences in the spectral reflectance of those objects. If a light source does not provide radiant power at those wavelengths where the spectral reflectances of those objects differ slightly, the objects will appear to have the same color. Therefore, a lamp that emits radiant power at all visible wavelengths would be expected to have good colour rendering properties. Among electric light sources, light from Xenon lamps most closely resembles a full spectrum. The same can be said for the 5500 K phase of daylight. Both of these sources have been experimentally shown to be excellent at revealing subtle differences in color that can not be seen under other types of lamp spectra. Light sources with deficiencies in some parts of the spectrum will have poorer FSI values and will be less effective at rendering subtle differences in object colours.

Gamut area (GA) is more commonly used in Japan than in North America. In principle, GA is defined as the area enclosed within three or more chromaticity coordinates in a given color space. GA is usually calculated from the area of the polygon defined by the chromaticities of eight CIE standard color samples in CIE 1995 color space when illuminated by a given light source. The CIE 1995 color space is used because equivalent distances in this color space are assumed to be "perceptually equal." In general, the larger the GA, the more saturated the object colors will appear.

Given the present state of knowledge about predicting the colour appearance of objects under different light sources, no single metric can capture the multidimensional aspects of colour rendering. In very general terms, a high colour rendering index (CRI) implies that colours will appear natural. A low full-spectrum index (FSI) implies that the light source will enable good discrimination between small colour variations. Finally, a large gamut area (GA) implies colours will be highly saturated.

3.2.5 Veiling reflection

Veiling reflections are luminous reflections from specular or semi-matte surfaces that physically change the contrast of the visual task and therefore change the stimulus presented to the visual system. (21) They depend on specularity of the material being viewed and the geometry between the observer, the target, and any sources of high luminance. The positions where veiling reflections occur are those where the observer's eye is reached by reflected rays coming from a source of high luminance. If the object is a perfect diffuse reflector no veiling reflections can occur. Glossy papers, glass surfaces and computer screens are subject to cause veiling reflections. In rooms with several computer screens special care has to be taken in the positioning of the luminaires to avoid luminous reflections from the screens. In using portable computers the viewing directions may change in relation to the fixed luminaires and this poses further requirements for lighting design. Also, when rearranging the working places and geometry of the working conditions, the possible causes of veiling reflections should be avoided in the typical viewing directions.

3.2.6 Shadows

Shadows occur when light from a particular direction is intercepted by an opaque object. (4) The effect of shadows can be overcome either by increasing the proportion of interreflected light by using high-reflectance surfaces or by providing local lighting in the shadowed area. If the object is small and close to the area of interest, the shadow can be cast over a meaningful area, which in turn can cause perceptual confusion, particularly if the shadow moves. An example of this is the shadow of the user hand while writing on paper as shown in ***Figure 9***.

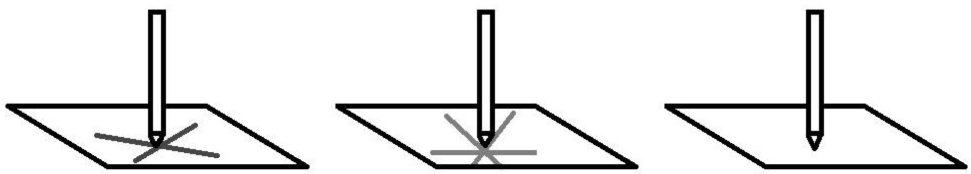

Figure 9 – *Example of shadows caused by a pencil in upright position in different lighting situations: two point sources, multiple large area sources, high interreflections.*

The number and nature of shadows produced by lighting installations depend on the size and number of light sources and the extent to which light is interreflected. The strongest shadows are produced from a single point source in a black room. Weak shadows are produced when the light sources are large in area and the degree of interreflection is high.

3.2.7 Flickers

The entire electric light sources that operate in AC produce a fluctuating output. If the fluctuations are visible the phenomenon is called flicker. General lighting installation that produces visible flicker will be almost universally disliked, unless it is being used for entertainment. The detection of the flicker depends on users' sensibility, so range of detection is wide and safety margins in flicker limits are necessary. The main variables that determine flicker perception are the frequency and percentage modulation of the oscillation in light output, the proportion of the visual field over which the flicker occurs, and the adaptation luminance.(21) To eliminate the perception of flicker, it is necessary to increase the frequency of oscillation above the critical flicker frequency or to reduce the percentage modulation of the oscillation, reduce the area of the visual field over which the oscillation occurs, or reduce the adaptation luminance. The most common approach is to use "flicker-free" ballasts with high-frequency control gear for discharge lamps and to mix the light from lamps powered from different phases of the electricity supply, both of which increase the frequency and reduce the modulation of oscillation in light output.

3.3 Eye strain

Lighting for vision during the day is quite adequate in most of the office buildings, in part because people have very flexible visual systems and adjust their posture in response to the available lighting conditions. Any visual task that has characteristics that place it close to threshold visibility has a high level of visual difficulty. Many experiments show that young people with normal eyesight will systematically adjust the eye-to-task spacing to maintain good task visibility, either by moving closer to the visual task or shifting posture to avoid reflected glare. A flexible visual system combined with a flexible body provides most people with the ability to adapt to less than ideal lighting environments. On the other hand, some portion of the adult population will likely have visual problems. Normal aging involves a continuous loss of visual accommodative ability, known as presbyopia. Instead of getting closer to an object people with presbyopia actually move the object farther away from their eyes, or they place it under a bright light, usually provided by a window or skylight. As the task is moved (brought closer or farther), the accommodation mechanism of the eye adjusts to keep the retinal image in focus. The continuous adjustments can lead directly to fatigue of the eye muscles, and indirectly to fatigue of other muscles caused by the observer adopting an unusual posture. Such muscle fatigue can produce symptoms of visual discomfort.(21) Long-term eye discomfort may lead to visual fatigue. Even if the concept of visual fatigue, so called asthenopia or eye strain, is quite old it has not a univocal definition since symptoms are many and non-specific (19). Its symptoms include irritated or itching eyes, headaches, diplopia (commonly referred to as double vision), spasms of facial muscles, conjunctivitis (otherwise known as pink eye), hot flushes, watering, increased nervousness and consecutively lower work performance(4). The overall tiredness is just a result of long-term eye strain, leading to loss of focus and attention. This can result in incorrect work practices and even injury. If employees feel several of such symptoms the work safety rules demand a medical assessment of their condition. Repeated eye strain is a cause to re-evaluate the lighting system in the workplace.

3.4 European standard EN 12464-1

To fulfil a visual task correctly and avoid visual discomfort the lighting system has to guarantee that the visual performance can be carried out well above the visibility threshold limits. To prevent overall tiredness and consequent injuries, the standards in EN 12 464-1:2011 “Lighting of work places – Indoor work places” (20) set up a framework depending on the demands of the job being carried out. Since lighting condition affect directly the visual performance, lighting systems have to be designed depending on the visual tasks to be fulfilled in that certain space. Visual tasks, and so the purpose of the space, have to be know in advance to be able to design the lighting system. The EN 12464-1 gives minimum requirements that workplace lighting and the direct environment needs to meet in order for the users to fulfil their visual tasks in an efficient, accurate and safe way. The standard presents a collection of tables stating the minimum requirements for the particular visual task. The requirements are expressed in terms of minimum required average illuminance per task, maximum URG, minimum uniformity and minimum required Ra.

In particular illuminance levels must not fall below the $\bar{E}_m$ maintenance values in the visual task area. If the precise location is not known, the limit should be applied to the whole room or a specific working area. UGR_L is the upper limit for direct glare. The UGR value calculated in the design process must lie below this. Uniformity U_O is the ratio between the lowest (E_{min}) and the mean illuminance level ($\bar{E}$) in the area. R_a is the lower limit for the colour rendering index. The R_a of the selected lamp must be equal to or greater than this value.

Table 1 *- Minimum requirements for lighting in offices stated out by EN 12464-1*

Ref.no.	Type of area, task or activity	$\bar{E}_m$ lx	URG_L -	U_o -	R_a -	Specific requirements
5.26.1	*Filing, copying, etc.*	300	19	0.40	80	
5.26.2	*Writing, typing, reading, data processing*	500	19	0.60	80	DSE-work
5.26.3	*Technical drawing*	750	16	0.70	80	
5.26.4	*Cad work station*	500	19	0.60	80	DSE-work
5.26.5	*Conference and meeting rooms*	500	19	0.60	80	Lighting should be controllable
5.26.6	*Reception desk*	300	22	0.60	80	
5.26.7	*Archives*	200	25	0.40	80	

3.5 Lighting Quality and Visual Comfort

Since the thirties of the past century, science of illumination has been a multidisciplinary field of study, strictly liked to the science of vision.(27) In fact the purposes of the research were already melting together and new ideas were spreading: "It is not sufficient to see, good vision is needed; the benefits of light are welcome, while risks are to be avoided; hygiene of sight is worthwhile, but also the health of the organism as a whole is to be taken into account" (28). Psychological effects were already considered in terms of motivation, satisfaction, aesthetics and pleasantness. Meanwhile managers started to wonder if and how the results of the scientific researchers could increase productivity, welfare and satisfaction of the workers. While the field of research was broadening, engineers decided that the best solution was considered only what was rigorously measurable, as for example illuminance, luminance, and contrast. Visual tasks have been divided into categories and standards, codes and recommendations have been set so that proper lighting of the workplace could be assured. The standards considered mostly threshold values, even if it was clear that the lighting in workplaces had to be well above the threshold limit. Efforts started to be put in finding a definition of lighting quality measurable by the mean of only one number. Researchers proposed many different methods, but soon became obvious that it couldn't be possible. Even nowadays there is not a complete and general definition of lighting quality and a lot of different definitions have been suggested in the past few years. The definition that seems most generally applicable is the one given by Boyce (4):

"Lighting quality is given by the extent to which the installation meets the objectives and constraints set by the client and the designer".

Objectives can be first of all avoiding visual discomfort, but also enhancing performance of relevant tasks, creating a specific impression, generating desire patterns of behaviour. The constraints can be related to standards, financial budgets, resources available, time-lines to complete the project, design approaches that have to be followed. This classification of light quality doesn't refer to any photometric measurements but, in Boyce opinion, there are three arguments in favour of this definition:

- Lighting is usually design and installed as a mean to an end, not as end itself. The achievement of the goal has then to be taken into account in the measure of the success.
- There are many physical and psychological aspects that can influence the perception of light quality so lighting quality cannot be define only from a visual performance point of view.
- Desirable light depends very much on the contest (social and cultural contest, visual tasks to be accomplished, etc.) so it is impossible to define lighting quality in a univocal and universal way.

Lighting quality is much more than providing the right amount of light and avoiding visual discomfort. Ensuring adequate and appropriate light levels (quantity of light) is only an elementary step in creating comfortable and good-quality luminous and visual environments. With a really simple description, lighting in an office can be qualitatively defined as bad, indifferent or good. Since lighting should be first of all designed to provide people with the right conditions that help them to perform visual tasks efficiently, safely and comfortably, lighting can be defined as bad if doesn't allow user to complete their visual tasks and causes visual discomfort, indifferent if allows users to quickly and easily see what they need to see and doesn't cause visual discomfort, good quality if, among all these aspects, it also "lifts the human spirit".(4) Lighting quality can be initially judged according to the level of visual performance required for activities and these is a visual aspect, but then there are also many physical and physiological factors that can influence the perception of lighting quality. For example lighting quality deals with psychological aspects when it is assessed on the basis of the pleasantness of the visual environment and its adaptation to the type of room and activity. In addiction there are also long term effects of light on our health, which are related either to visual aspects (the strain on our eyes caused by poor lighting), or to non-visual aspects, like the effects of light on the human circadian system.

The lighting design process can be then divided into two steps. The first one aims to achieve standards requirements, assuring that the lighting quality is not bad and so that the standard users can properly fulfil their visual tasks. The second step takes into account the real human being that will work in that space, trying to predict how he/she will perceive, live and react to the lit area, trying to assure a lighting system with good lighting quality. The first step procedures are already well known and defined, even if visual tasks in offices change over time and standards need to be often updated. Second step applications are way broader and subject of many present researches.

3.6 New offices and new visual tasks

The introduction of computers in the workplace has dramatically changed the lighting office design. In the 1980s and 1990s, issues pertaining to reflections and reflected glare on computer monitor displays prompted the development of dedicated lighting recommendations. But as the nature of office work has changed, to become more focused on computers and screen-based tasks coupled with newer display technologies and today's energy-efficiency criteria, what was once standard practice for office lighting has also evolved (29).

The first type of computer screens used was cathode ray tube (CRT), a technology inherently reflective. CRT monitors generate images by using an electron gun to shoot streams of electrons across a glass surface coated with millions of phosphor dots. These phosphors are white and very reflective. Therefore essentially all CRTs have some form of anti-reflective coat. Given how reflective CRT monitors are, office illumination designed in the 1980s and 1990s prioritized minimizing glare and ensuring visual performance. Vertical illuminance levels for screens were kept between 50 and 100 lx for optimal visibility. Lamps were shielded and luminance limits were established for direct lighting at high angles between 65 and 90 degrees (1000 cd/m^2 or 200 cd/m^2, depending on the screen quality). Low-glare lenses and louvers were commonly used. In workstations, the strong directional lighting required task lighting to eliminate shadows under shelves. Indirect lighting offered another option for eliminating glare. The light reflected off the ceiling was softer, less bright and therefore more accommodating of VDTs. Fixture spacing was optimized to ensure uniform illumination. The sharp cut-off, however, resulted in a cave effect and a gloomy office environment.

Few CRT monitors are still in use today, having been replaced by brighter and less-reflective technologies. Of these technologies, LCD (liquid crystal display) is the most widely used in desktop monitors, laptops, tablets, and cell phones. These displays also tend to be the brightest, achieving luminance of 300 to 450 cd/m^2, compared to 100 to 250 cd/m^2 for both CRTs and plasma screens. LCDs owe their high luminance to an independent backlight, the front polarizer absorbs and blocks ambient light, and the liquid crystal itself is a clear liquid, rather than a highly reflective white phosphor. Anti-reflectance treatments have proven effective in eliminating reflected imaging, and higher internal brightness and increased contrast have improved screen visibility, even in elevated ambient light situations. Such developments have pushed standards and lighting guidelines to evolve.

In the EN12464-1:2011 standard, compared to EN12464-1:2003, new luminance limits are defined for luminaires used with flat panel displays (display screen equipment DSE), because display screen technology has advanced, the limits are looser in the 2011 edition. Two limits are specified for ordinary office tasks depending on the luminance of the background:

- For display screens where background luminance is L <200 cd/m², luminaires luminance needs to be limited to a maximum value of 1,500 cd/m².
- For screens where background luminance is L >200 cd/m², luminaires luminance up to 3,000 cd/m² are permissible.

For new flat screens, manufacturers generally indicate maximum adjustable background luminance L >200 cd/m² but in practice the screens are mostly operated at L<200 cd/m². What is more, the background luminance that is subsequently set is not known at the design stage. In such cases, the luminance of the luminaires used should not exceed 1500 cd/m². Lower limits are set for more demanding visual tasks at a DSE work station (e.g. CAD): L ≤ 1000 cd/m² for display screens where background luminance is L <200 cd/m².

The luminance limits are specified for inclination angles between 90° and 65° in any radiation plane in order to avoid reflections on vertical to 15° tilted screens. The values specified apply to flat-screen monitors with a good anti-glare finish, which are used at most office work stations today. No longer confined to luminaires with low brightness or indirect lighting, the designers are able to design different types of lighting and alleviate some of the earlier gloominess associated with office lighting design.

Nowadays office culture is changing again. As a generation of digital natives arrives in the workplace, having grown up with smart phones and tablets, offices have had to adapt to provide the right working conditions for them (30). Tablets and smart phones screens are LCD as well but, aiming to clarity and vibrant colours, they tend to have a glossy finish to enhance their sensitivity to touch. The actual image contrast, screen visibility, and readability of tablets and Smartphone screens depend on a combination of both the display's brightness and the screen's reflectance. Unfortunately manufacturers have done very little to improve screen reflectance and sometimes this screens are real mirrors.

Moreover tablets and smart phones tend to be held at angles that pick up more of the surrounding ambient light than the more vertically oriented screens in laptops and desktops (***Figure 10***).

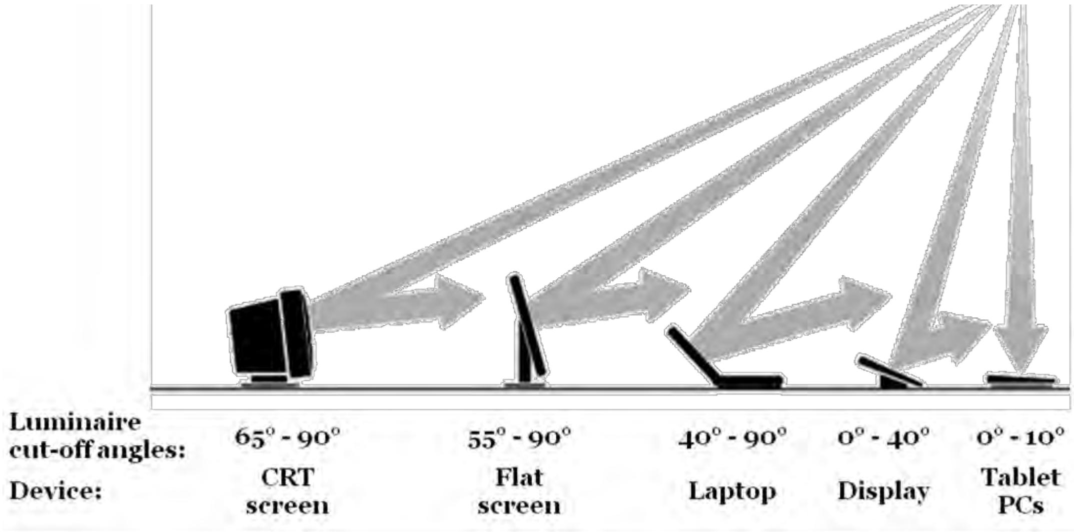

Figure 10 *- Luminaire cut-off angles for different types of screens* (31)

The standards requirements do not apply to notebooks, laptops, tablet PCs or similar devices. The main idea is that, since these screens can be set up at any angle in any direction, disturbing reflections can be avoided by adjusting the position of the screen. Nevertheless some luminaire manufacturers start to think about glare control on modern displays (31). Taking into account changing work media (such as laptops and tablet PCs), new radiation angles that can cause glare have been identify. Especially for luminaires arranged directly above workstations luminance for steep viewing angles can be reduced to limit glare reflected from steeply inclined displays like laptops or tablet PCs and increase visual comfort.

4 . Lighting retrofits

The building retrofit optimization problem is to determine, implement and apply the most cost effective retrofit technologies to achieve enhanced energy performance while maintaining adequate service levels (...) under a given set of operating constraints. (Z.Ma et al. Existing building retrofits: Methodology and state-of-the-art. Energy and Buildings. 2012)

Retrofit is defined as "work required to upgrade and aged or deteriorated building to meet new requirement" (2). From the lighting point of view these requirements are for example reaching energy consumption and efficiency standards, increasing lighting quality, achieving economical savings. In this chapter the general procedure to plan and realize a lighting retrofit is presented. The key approaches described have a general validity while the technologies that provide the foundation for these strategies improve every year and change over time. Nevertheless efforts have been put in trying to give an overall description of the present technology options.

4.1 Key phases in a lighting retrofit programme

To effectively conduct a lighting retrofit project the following tasks should be fulfilled (2):

- **Lighting and daylighting audit:** Lighting audit is used to understand the building energy consumption in lighting and identify the areas where energy is wasted. This phase plays an essential role in lighting retrofit projects because it identifies areas with savings potential and provides the parameters to choose the best retrofit strategy. The saving potentials of each space are measured with appropriate instruments and tools; performance assessments take into account both the installed lighting power (wattage) of each space, the typical daily hours of use, usage patterns and users experiences.
- **Prioritize the possible retrofit works**: in this phase the building owners or their agents need to define the scope of the retrofit project and set the targets according to the site needs and owners' budget. The possible retrofit works are prioritized according to their energy savings potential and ease of the retrofit

process. To priorities the retrofit measures a reliable estimation of the possible energy savings is indispensable.

- **Identify suitable strategies and technologies options**: By the use of appropriate energy models and economic analysis tools, suitable retrofit strategies and technologies options are identified and compared. Depending on the targets, the features of the different retrofit options to be taken into account can be: energy savings potential, economic returns, ease of installation, overall longevity of the option, increased level of lighting quality. There are a numbers of different energy simulation packages that can be used to simulate the lighting and energy performance to different retrofit strategies. An extensive list of software and tools can be find in the Building Energy Software Tools Directory (32). DOE (United States Department of Energy) created this directory of software tools to help people involved in the building life-cycle to evaluate and rank potential energy-efficiency technologies and renewable energy strategies in new or existing buildings.
- **Implementation:** the selected retrofit strategy will be implemented. While planning the implementation, the duration of the works have to be taken into account to avoid significant interruptions and problems to the building and users operations. Particular attention has to be paid in tuning the retrofit measure (i.e. occupancy sensors) in order to ensure the lighting system to operate in an optimal manner.
- **Verify results:** after the implementation of the retrofit strategies the actual energy saving and other improvements are measured to verify the fulfilment of the goals. A post retrofit survey is also needed to attest if the building users and owners are satisfied with the overall result.

4.2 Available lighting retrofit strategies for offices and savings potentials

Although today there are many retrofit technologies available, identifying the best retrofit option for a particular project is still a technical challenge, since the selection of the retrofit strategy should be based on the very specific office characteristics, project budget and usage patterns.

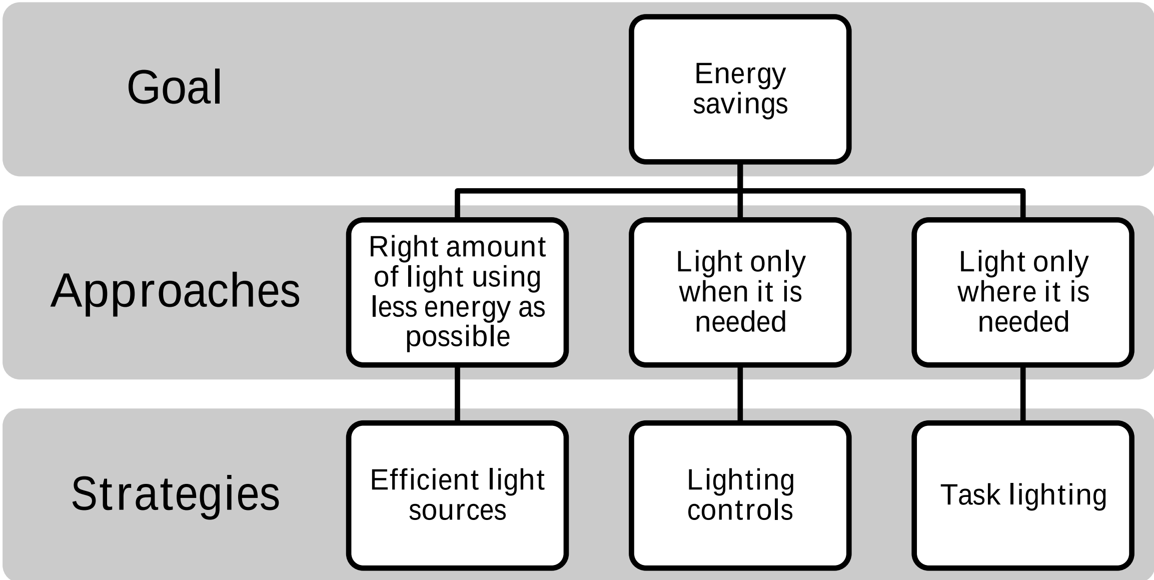

Figure 11 *- Approaches and strategies in lighting retrofits to achieve energy savings, as resumed from* (4)

The previous diagram shows the main approaches used in lighting retrofits when the goal is achieving energy savings. To find the best retrofit option all the approaches have to be taken into account and the new lighting solution will be a system that integrates different strategies. Only strategies concerning the retrofit of the electric lighting system have been considered. Other retrofit strategies, concerning for example windows and shading devices, can increase the exploitation of daylight and produce additional savings but they have not been studied in this thesis.

4.2.1 Efficient light sources

In 2005 the most used light sources in the tertiary sector were linear fluorescent lamps (8), as described by Figure 12. In general, lighting in office spaces was achieved with a regular array of recessed or surface-mounted multi-lamp fluorescent luminaires or pendant-configured direct/indirect luminaires. The fluorescent lamps mainly used in the last decades were standard T8 and T12 in a variety of different types, wattages, colour temperatures and colour rendering indexes. The reason for this popularity is that they had quality light output, were one of the most efficient light sources available, and had decent lifespans. This is especially true of the T8 lamps, which use about 40% less energy than the now phased-out T12 lamps.

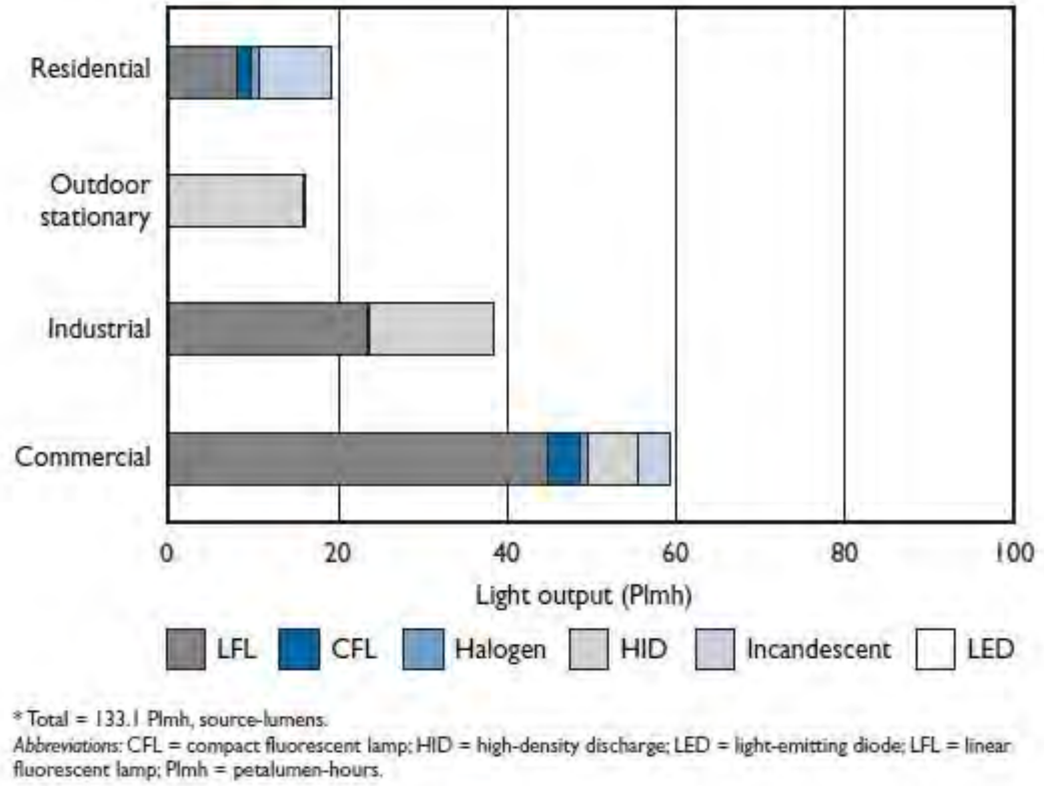

***Figure 12** – Estimated global average share of electric light production by lamp type and end-user sector in 2005* (8)

Nevertheless nowadays many of these installations are outdated and need to be relamped. The selection of more efficacious light sources is a decision involving a number of factors, such as the current condition of the existing fluorescent lighting, power density, presence of lighting control systems, and economic considerations. The main alternatives to standard T8 and T12 include T5 fluorescent lamps and solid-state LED technology. In the following table suitable alternatives for a standard T8 1200 mm lamp are compared. Data come from the analysis of multiple data sheets of different producers (Philips, Osram, GeLighting).

***Table 2** – Comparing lamps suitable for a standard T8 1200mm lamp retrofit.*

	standard T8 (baseline)	**T5 high efficiency fluorescent lamps**	**TLEDs**
Instant Fit In T8 Socket		no	yes
Wattage	36	25, 28	12 - 21
Luminous Flux	2230 - 3100	2400 - 3000	1000 - 3000
Efficacy (Lm/W)	90 - 110	90 - 115	80 – 100
Average Life (Hr)	24.000 - 45.000	14.000 - 36.000	30.000 - 70.000
Colour Rendering Index CRI	80 - 90	80 - 90	65 - 90
Temperature	Fluorescent lamps work ideally at normal to warm temperatures. Best efficiency at 25 degrees	Best efficiency at 35 degrees.	LEDs need to stay cool. With temperatures higher than 65 to 70 degrees, the life span will decrease significantly.
Controllability (Frequent Switching)	When the lamp is switched on and off frequently it will age more rapidly.		The aging of an LED is not affected by switching it on and off.
Instant Start	At first use, fluorescent lamps have burn for several hours to reach full capacity. When used with instant-start ballast, they will start up immediately. When used with rapid-start ballast, they will start with 1.25sec delay.		LEDs do not have to warm up and will switch on immediately.
Hazardous Substances	1.8 - 3 mg mercury.	1.4 - 3 mg mercury.	LEDs don´t contain hazardous substances.
Average Cost Per Lamp	0.5-5 €	5-10 €	10-30 €

The following relamping/retrofitting approaches are available today for existing linear fluorescent luminaires(33):

Relamping with T5 fluorescent lamps

Since T5 lamps are smaller than T8 lamps and use a miniature bi-pin base, T5 tubes need an adapter to be fitted in the existing sockets. Conversion kits are available and often they contain high frequency new ballasts. The magnetic ballast remains in place but it is bypassed, becoming ineffective as a conductor. The new high-frequency ballast draws only 2 W, rather than the 6-10 W of the old ballast, increasing the efficiency of the system. The relative saving potential due to improvement of lamp and ballast technology are around 20%.

Relamping with tubular LED lamps

As Table 13 shows, LEDs offer a lot of advantages if compared to fluorescent lamps, especially in terms of ease of control and lifespan. The only major downside with T8 LEDs is their cost, which can be five to ten times greater than the price of LFLs. Since LED tubes and LFLs uses two different types of light sources many factors have to be taken into account while planning a relamping (34):

- ***Luminous output:*** LED tubes and LFLs have different light flux outputs. Additional tubular LED replacement lamps may be needed to reach the same lighting level which would decrease the potential energy savings of retrofitting. This won't happen in spaces that are over-lit or in those retrofit projects that introduce task lighting to supplement general lighting.

- ***Light distribution:*** Tubular LED lamps incorporate multiple, directional light sources into a linear form. As a result, tubular LED and linear fluorescent lamps installed in the same housing can produce different light distribution patterns (35) as shown in **Figure 14** and **15**.

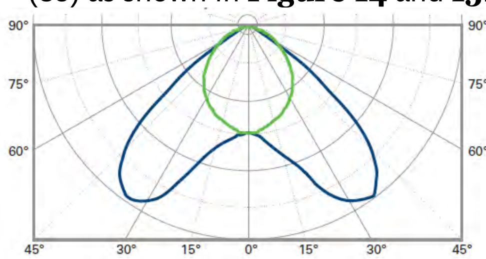

Figure 14 *- Intensity distribution, linear fluorescent lamp [33]*

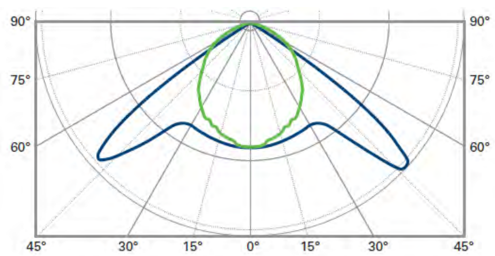

Figure 15 *- Intensity distribution, LED tube with diffuser [33]*

Ballasts and drivers: Differently from fluorescent lamps, LEDs don't need a ballast to operate. Therefore to fit LED T8s into existing linear fluorescent fixtures, a way to deal with the unnecessary ballasts is needed. A tubular LED lamp retrofit will include a replacement or bypass of the existing fluorescent ballast with a dedicated, hardwired electronic driver that supports dimming control. This permanently and safely reconfigures the tombstones for an LED tube lamp.

Currently there are three types of LED T8s on the market suitable for retrofits. They are differentiated by how they interact with existing ballasts. These solutions include bypassing the existing ballast, removing it, or working with it.

The first type of LED tubes has an internal driver that makes it possible for the lights to use existing electronic ballasts and fixtures. They plug directly into the most common linear fluorescent setups so the installation is quick and easy. The main disadvantage of this type of LED tubes is that their life depends on the longevity of the ballast. This can result in more maintenance costs if compared to other LEDs, since the electronic ballast will have to be replaced before the LED tube has reached its lifetime. Moreover they are compatible only with instant-start electronic ballasts, some power is lost from integration with the ballast and dimming and other types of energy-saving functionalities are limited. (34)

The second type of LED tubes has an internal driver so the ballasts are removed from the fixture and the power is wired directly to the sockets. This solution is more efficient since no power is wasted in the ballast and need less maintenance. On the other hand electrical modifications are required: removing the ballasts, possibly replacing the sockets and rewiring. The installation can be dangerous since installers could be exposed to main voltage while connecting sockets to power wires. [32]

The third option is using a remote driver to power the LED so that one driver can power multiple LED tubes. Electrical modifications are still required since the ballasts have to be removed but the operation is much safer, since the low-voltage driver is connected to the sockets and not the line voltage. This type of LED tubes is the most efficient and they can fit in any fluorescent fixture. Moreover they are easily dim and controlled. Nevertheless the installation costs and time are high. [32]

Retrofitting with new LED luminaires

This retrofit approach involves replacing existing fluorescent luminaires with new LED luminaires that have been designed specifically for operation with their solid-state light sources. This completely dedicated design offers the best opportunity for consistent and superior photometric performance, safety, longevity, and savings (energy and money). Retrofitting with an entirely new LED luminaire will most likely be the most expensive option in terms of initial project costs, but over the life of the product, the incremental cost associated with using new LED luminaires is actually very small compared to the lamp replacement. [32]

4.2.2 Lighting controls

Lighting controls help to ensure that light is delivered at the right levels for particular areas only when required so that a reduction of energy consumption can be possible without compromising visual comfort. Energy savings are achieved because the control reduces the operating hours and watts used when the light is on (dimming). (3) Lighting controls can be used for a range of applications such as presence detection and daylight harvesting. ***Figure 16*** shows effective strategies for lighting control (36).

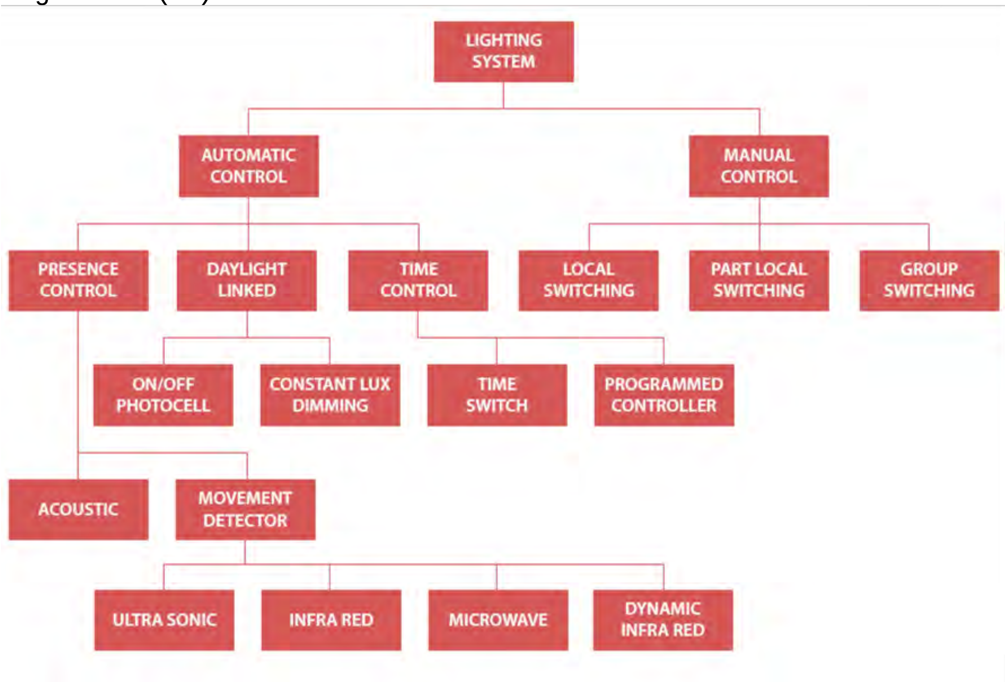

Figure 16*- Effective strategies for lighting control*

Occupancy Sensors

Operating hours of the lighting system can be reduced by adjusting lighting according to the real occupation of the area. In fact lights frequently are left on in unoccupied places where there is no need for them. This especially happens in rooms which are used infrequently (occupancy rate <50%, for example meeting rooms), areas where the users have no control on the lighting system (corridors and staircases) or rooms where people entering have their hands free and upon exit have their hands full (storage rooms). A lighting solution equipped with occupancy sensors switches off or dims down when a person leaves the field of a sensor. The lighting is switched on by the user (personal control) or by the system when detecting a person entering the field of the sensor. Energy savings between 18 and 60% are found in a number of fields. Energy savings depend on the level of detection, place of the sensor and the movements of the users. The detection area depends on the type of sensor used (infrared, ultrasonic, microwave); it can vary from 6 to 15 m for each sensor.

User acceptance of the systems depends largely on the delay time, the time period between detecting vacancy and switching off the system. Although larger savings can be achieved with short delay times (a few minutes), the system might switch off because occupants are not moving around. Appropriate delay times, as well as appropriate technology and correct position of the occupancy sensor are of importance to ensure user acceptance.

Daylight linked control

The daylight harvesting control strategies aim to reduce energy consumption using daylight and juxtaposing artificial lighting only when needed to maintain the required lighting level. The possible control strategies of the lighting system are two: on/off switching or constant illuminance dimming. Photocells are used to measure lighting levels, if the level is too high the system controller dims or switches off the lights, if the level is too low the controller increases the lumen output of the electric light source or switches it on. With fluorescent luminaires the on/off switching allows the use of non-dimmable ballasts that are more efficient but, on the other hand, the switching can create dramatic changes in the light level and distract the occupants.

Daylight harvesting system is mainly used in areas with wide windows. In large areas sensors often control separate groups of lights in order to maintain a uniform lighting level throughout the area. The luminaires in each zone can then adjust lighting levels depending on the natural light entering the space, minimizing lighting energy use while maintaining uniform lighting levels. The savings potential varies from 20% (daylight-harvesting alone) to more than 60% (daylight harvesting plus real occupancy).

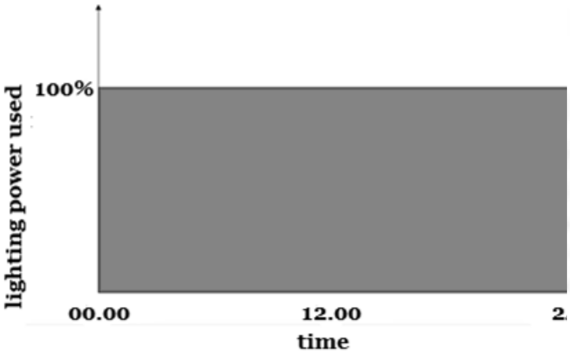

***Figure 17** – Office lighting power usage with no control*

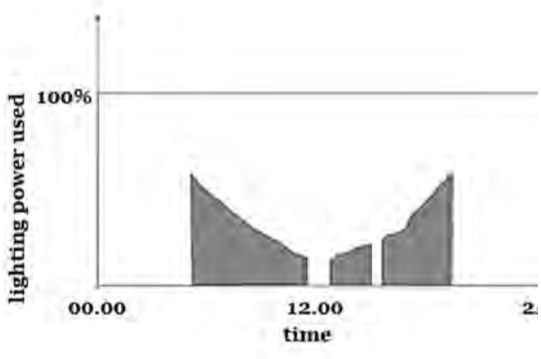

***Figure 18** – Office lighting power usage with occupancy and daylight harvesting controls*

In the figures above a simple example of lighting controls in an office is presented. The first picture shows the energy consumption in the worst possible scenario: lights full on for 24 hours per day. The second picture shows the possible savings achievable by the use of both occupancy and daylight harvesting controls.

Many lighting retrofits have been monitored and studied to asset the energy savings achievable thanks to effective lighting controls. For example Galasiu et al. in (37) conducted a field study in a deep-plan office building equipped with suspended direct-indirect luminaires. To achieve energy savings integral occupancy sensors and daylight sensors were employed. Data collected from 86 workstations over a year showed that the lighting control generated substantial energy savings and peak power reductions compared to a conventional fluorescent lighting system installed on a neighbouring floor. The controls combined saved 42 to 47 percent in lighting energy use compared to the same lights used at full power during work-hours.

4.2.3 Task lighting

The lighting design of workplaces is mainly regulated by the European standard EN 12464-1 “Lighting of work places – Indoor work places”. This standard concerns minimum requirements that workplace lighting and the direct environment needs to meet in order for the users to fulfil their visual tasks in an efficient, accurate and safe way. Standard compliant lighting is no guarantee in itself for good lighting. For this, application know-how, product know-how and an understanding of the customer’s situation are required.

The main feature of this standard is that it highlights the illuminance requirements of the actual working area rather than the entire room. Defining what is the task area and the immediate surrounding gives the designer the freedom to separate the elements of task area from the environment/background and to light them differently. The task area is lit according to the visual requirements set by the standard. The standard presents a collection of tables stating the minimum requirements for the particular activity. The requirements are expressed in terms of minimum required average illuminance per task, maximum URG (unified glare rating), minimum uniformity and minimum required Ra (colour rendering index).

Table 3 *- minimum requirements for lighting in offices stated by EN 12464-1*

Ref.no.	**Type of area, task or activity**	**$\bar{E}_m$ lx**	**URG_L -**	**U_o -**	**R_a -**	**Specific requirements**
5.26.1	*Filing, copying, etc.*	300	19	0.40	80	
5.26.2	*Writing, typing, reading, data processing*	500	19	0.60	80	DSE-work
5.26.3	*Technical drawing*	750	16	0.70	80	
5.26.4	*Cad work station*	500	19	0.60	80	DSE-work
5.26.5	*Conference and meeting rooms*	500	19	0.60	80	Lighting should be controllable
5.26.6	*Reception desk*	300	22	0.60	80	
5.26.7	*Archives*	200	25	0.40	80	

The required minimum average illuminance on the task is specified by the standard. If the entire room is not considered as a whole task area but individual task areas are lit, the illuminance of the immediate surroundings can be one step lower. The steps have been defined in the standard as:

20-30-50-75-100-150-200-300-500-750-1000-1500-2000-3000-5000 (values in lx)

With regard to an office application, this gives the following alternatives:

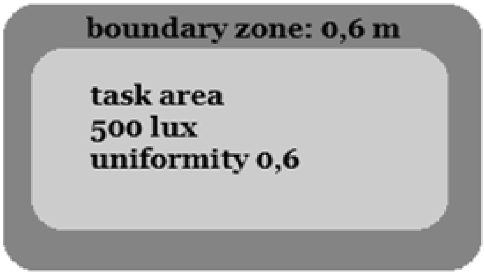

Figure 19 *- the complete room is the task area*

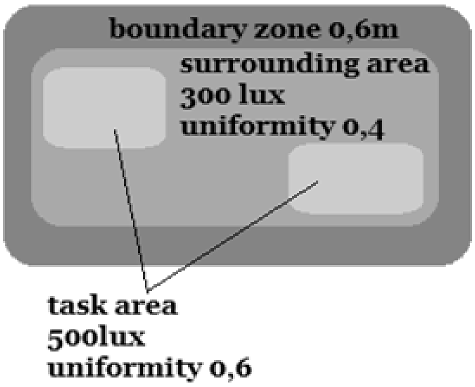

Figure 20 *- multiple task areas*

The second alternative requires a less amount of light compared to the first one and if the lighting system is accurately designed significant energy savings can be achieved. For instance a task/ambient lighting system can be used where a combination of electric light and daylight could light the environment area and electric task lighting like individual task lamps could provide higher localized illumination. The use of task/ambient lighting has a relative savings potential of 22/25% (6).

To demonstrate that task-ambient lighting can fulfil energy savings many light retrofits have been monitored. An example is the retrofit project conducted at the University of California (38). The studied area was a 9,000-square-foot open office. In the existing baseline the ambient lighting was given by fluorescent pendants using standard 32 W linear T8 fluorescent lamps. Since the illuminance levels on the task area were not adequate, occupants were using fluorescent/incandescent personal desk lamps. Total energy consumption was 76 567 kWh per year. In the retrofit project standard linear T8 fluorescent were replaced with super saver T8 fluorescent lamps. In addiction LED task lighting with personal occupancy sensors was added for each work station. After the retrofit the energy consumption has been 33 064 kWh per year, 57% less than the baseline.

4.3 Conclusions

In this Chapter three main strategies to achieve energy saving in lighting retrofits have been presented: use of more efficient light sources, use of light controls and use of task/ambient lighting. The final energy savings realized by a light retrofit depends on many factors: baseline consumption, technologies chosen, integration of different strategies, users' usage patterns, and many others. Integrating different strategies it is possible to achieve higher energy savings.

The relative saving potentials achievable with each retrofit strategy are summarized in the following table (6).

Table 4 *– retrofit strategies and relative energy savings potential*

Retrofit strategy	**Average energy saving potential**
Efficient light sources	10-40%
Use of light controls	20-60%
Use of task lighting	22-25%

5 . Case study

Since artificial light has become highly controllable in quality, quantity and distribution we have the need of and the opportunity to develop a new science: Seeing.
(Dr.M.Luckiesh and Frank K.Moss: Light for seeing. General Electric Co. 1931)

5.1 Aim of the study

The aim of this case study is to provide an example of monitoring method for a lighting retrofitting project and to quantify the energy savings achieved thanks to the installation of the new lighting source technology and to the active dimming control system. Six offices have been studied and two different analyses have been carried out. The first analysis deals with the comparison between pre and post retrofit conditions in each room. The second analysis compares two different retrofit strategies: new luminaires with or without active dimming controls. Rooms lighting conditions have been described from three different points of views: energy consumption of the lighting system, light environment and user satisfaction. In this way not only energy and economical savings have been studied but also improvements in the level of lighting quality.

5.2 Retrofitting project

Between September 2014 and February 2015 six offices in the building of Electrical Engineering of the Aalto University have been study. The building is located in Otakaari 5, Otaniemi Campus, Espoo, Finland (Latitude: 60.189342, Longitude: 24.831226). Three of the rooms were on the third floor and the other three at the forth. The six offices have the same area and configuration and almost the same furniture disposition as shown in Figure 21 .

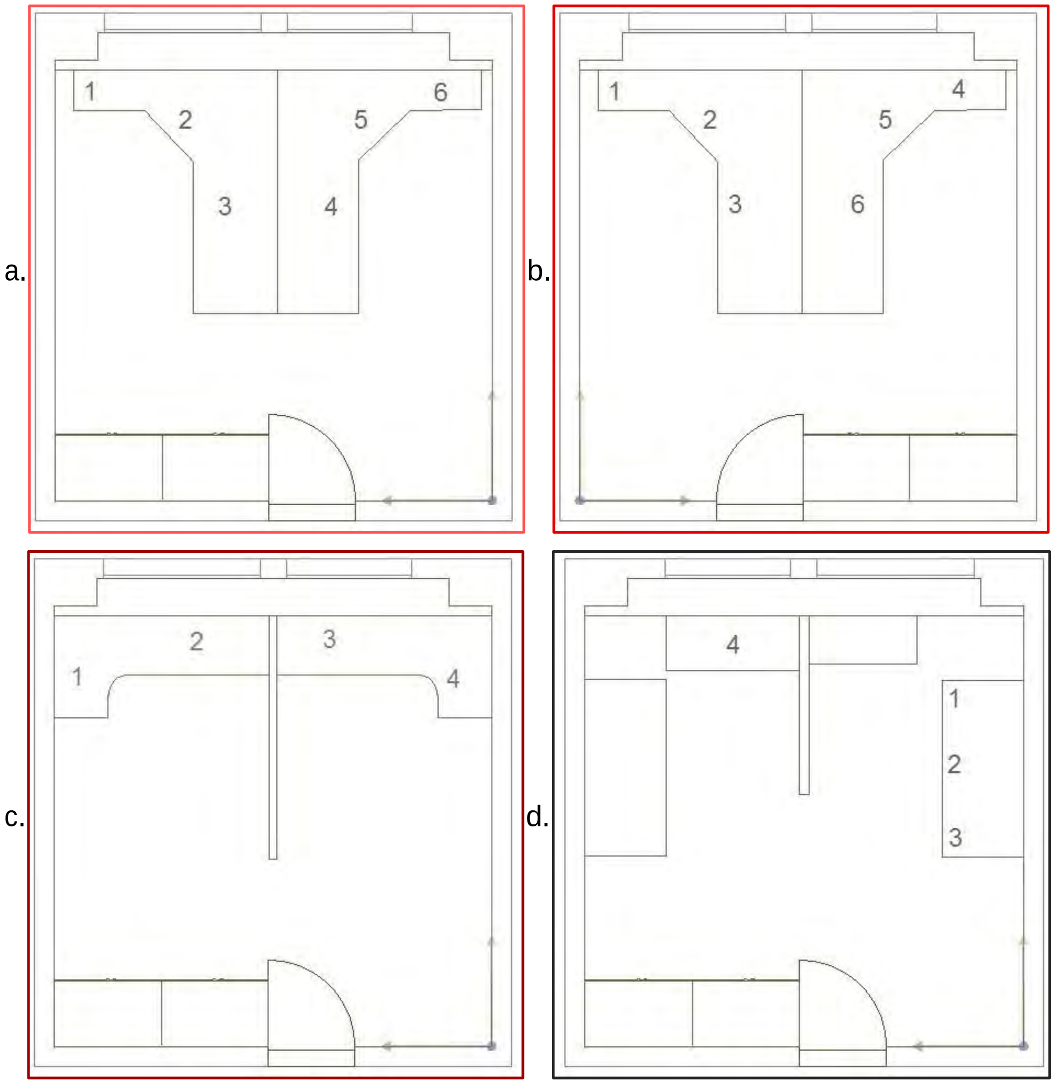

Figure 21 *– Case study rooms configuration. Two rooms were like a.; two like b.; one like c.; one like d.*

The original lighting system of each room consisted in four T8 fluorescent luminaires. Luminaires were more than 40 years old. In the past years lamps have been substituted many times and also the reflector had been once substituted. All the other parts of the luminaires (including ballasts) were original.

In each room there were two different types of luminaire: two troffers with two lamp slots and two troffers with three lamp slots. Nevertheless only one T8 fluorescent lamp was installed in each luminaire. The operation of the luminaires with just one lamp was possible thanks to the appropriate shape and reflectance of the new reflector. Luminaires were disposed as shown in Figure 22. The old luminaires are described in details in Table 5.

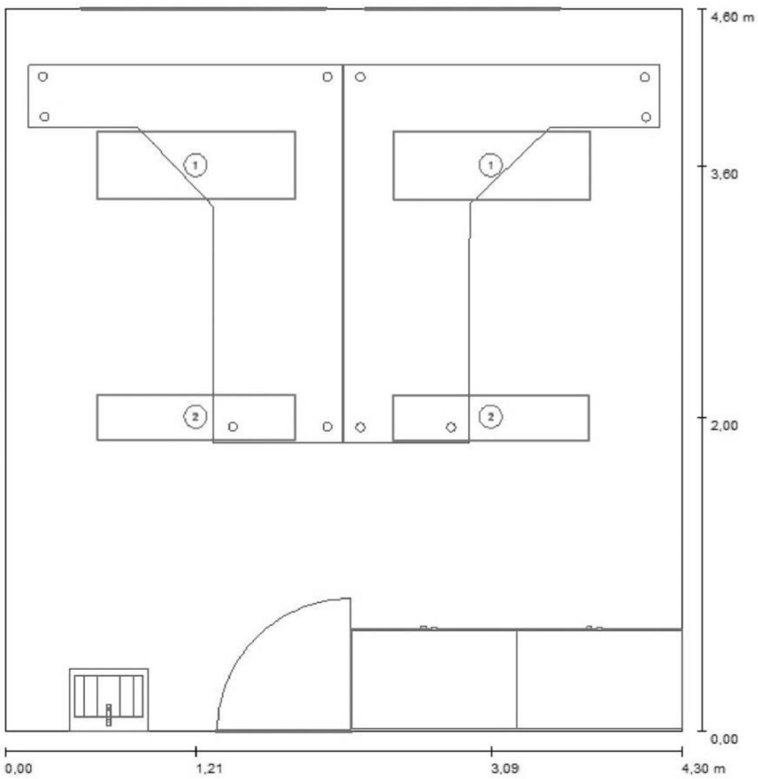

Figure 22 *– Old lighting system configuration.*

Table 5 *– Old lighting system description*

	Lamp Slots	**Dimensions (l*w*h)**	**Ballasts**	**Lamp**	**Type**
Troffer 1	3	125*43*11 cm	Helvar L40G	PHILIPS TLD 36W/830	Fluorescent
Troffer 2	2	125*29*11 cm	Helvar L40G	PHILIPS TLD 36W/830	Fluorescent

It is important to highlight that old luminaire ballasts were Helvar L40G. Helvar L40G is an old magnetic ballast classified as D class (magnetic ballasts with very high losses, system power >45 W) in the EEI rating system. According to European Directive 2000/55/EC (13) this type of ballast is banned from the market since 21.05.2002, in other words its use has been phased out.

In two of the rooms the old troffers have been retrofitted with new LED luminaires. In similar two rooms LED luminaires with active dimming were installed. The new luminaires have been installed in the same position of the old ones. The remaining two rooms have not been retrofitted and they rooms were left as reference rooms with the old lighting system (fluorescent luminaires). The features of the new luminaires are presented in Table 6.

Table 6 – *Old lighting system description*

	Luminaire	Dimensions (l*w*h)	Nominal Power	Control	Sensor	Type
LED luminaire without dimming	AIL1543F LED 40W/840 AC F	143*7*7,5 cm	40 W	Manual	-	LED
LED luminaire with active dimming	AIL1543FED LED 35W/840 AC F DA	150,2*7*7,5 cm	35 W	iDIM active solution	Helvar minisensor3	LED

The Helvar "iDIM active" active dimming solution used in two of the six rooms consists in a stand-alone inbuilt dimming solution for LED luminaires. (39) It is a system of different components: iDIM Solo (interface module and DALI power supply), LED driver and Minisensor3 shown in Figure 23.

Figure 23 – *Helvar "iDIM active" components* (39)

Helvar Minisensor3 is a two channel luminaire-mounted component containing three integrated sensors: Presence detector (PIR), constant light sensor and infrared (IR) receiver to remotely control it (40). The explanation of the sensors functioning is explained in Chapter 4.2.2. ***Figure 24*** shows the detection areas of both the sensors.

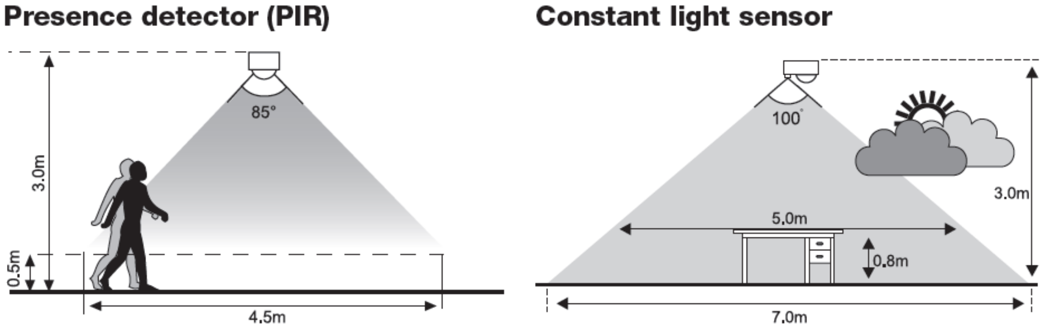

Figure 24 *– Minisensor3 detection areas* (40)

The installation procedure of the luminaires with active dimming control was exactly the same as the installation of LED luminaire without control system. In fact the active dimming control system is inbuilt in the luminaire so there was no need to install extra wires for control, and the old electrical installation was used as power supply for the luminaires.

After the retrofit, two energy meters have been installed in two rooms to measure the light consumption of the new lighting systems. One of the energy meter measures the consumption of a lighting system without dimming control, the other measures the energy consumption of a lighting system with active dimming control.

5.3 Monitoring the retrofit: Methods and needed data

5.3.1 Energy efficiency and consumption

According to the European standard EN 15193 “Energy performance of buildings - Energy requirements for lighting” (17), there are two methods to assess the energy consumption of a building: the calculated method and the metered method. Energy consumption of the lighting system has to be assessed in both pre- and post-retrofit conditions. Before the retrofitting any power meter on dedicated lighting circuits were installed so the calculated method has been applied. After the retrofitting, kWh-meters have been installed in one room without dimming control and in one room with active dimming control. The metered energy consumption data cover so far only three winter months operation. These data have been used for a weekly and monthly analysis of the post retrofit energy consumption and for a comparison between lighting system with and without lighting controls. Nevertheless for an annual analysis of the energy consumption the calculated method has been used also for the post retrofit condition.

According to EN 15193 calculated method the estimated required energy in a room for a certain period shall be estimated by the following equation:

$$W_{\mathrm{t}} = W_{L,t} + W_{P,t}\ [kWh] \qquad (5.3)$$

Where:

- $W_{L,t}$ = energy required to fulfil the illumination function and purpose
- $W_{P,t}$ = parasitic energy required to provide charging energy for emergency lighting and for standby energy for lighting controls

$W_{L,t}$ shall be established using the following equation:

$$W_{L,t} = \sum\{(P_n \times F_c) \times [(t_D \times F_O \times F_D) + (t_N \times F_O)]\}/1000 \ [kWh] \quad (5.4)$$

Where:

- P_n = total installed lighting power in the room or zone $Pn = \Sigma P_i$ [W]
- F_c = constant illuminance factor, factor relating to the usage of the total installed power when constant illuminance control is in operation
- t_D = daylight time usage, operating hours during the daylight time, measured in hours
- F_o = occupancy dependency factor, factor relating the usage of the total installed lighting power to occupancy period in the room or zone
- F_D = daylight dependency factor, factor relating the usage of the total installed lighting power to daylight availability in the room or zone
- t_N = non-daylight time usage, operating hours during the non-daylight time, measured in hours

$W_{P,t}$ shall be established using the following equation:

$$W_{P,t} = \sum\left\{\{P_{pc} \times [(t_y - (t_D + t_N))]\} + (P_{em} \times t_{em})\right\}/1000 \ [kWh] \quad (5.5)$$

- P_{pc} = total installed parasitic power of the controls in the room or zone, input power of all control systems in luminaires in the room or zone when the lamps are not operating, measured in watts
- t_y = standard year time, 8 760 h
- t_D = daylight time usage, operating hours during the daylight time, measured in hours
- t_N = non-daylight time usage, operating hours during the non-daylight time, measured in hours
- P_{em} = total installed charging power of the emergency lighting luminaires in the room or zone
- T_{em} = emergency lighting charge time, operating hours during which the emergency lighting batteries are being charged, measured in hours

European standard EN 15193 define the Lighting Energy Numeric Indicator (LENI) as

$$\text{LENI} = \frac{W_t}{A}\left[\frac{\text{kWh}}{\text{m}^2 \times \text{year}}\right] \quad (5.6)$$

Where:

- W_t=total energy used for lighting
- A=useful floor area

LENI is the total energy used for lighting per year per m^2. The standard EN 15193 sets limit values for LENI depending on the features and usage of the room. However EN 15193 and LENI focus only on the energy consumed but not on the efficacy with whom this energy is transformed into light and on the amount of light that is present in the room.

Therefore, to study the energy efficiency of a lighting system, it is important to take into account also other factors, like luminous efficacy. Luminous efficacy (η) of a luminaire is a measure of how well the luminaire produces visible light. It is the ratio of luminous flux (F) to the input power (Pi).

$$\eta = F/Pi \text{ [lm/W]} \tag{5.7}$$

Needless to say that, if the luminous flux is set, the greater is the efficacy the less energy is used to produce the same amount of light, so the smaller is the energy consumption.

Pre-retrofit conditions

In pre-retrofit conditions there were no automatic controls, no dimming and no emergency lights so:

$$\begin{aligned} W_\mathrm{t} = W_\mathrm{L,t} &= \sum \{(\mathrm{P_n} \times \mathrm{F_c}) \times [(\mathrm{t_D} \times \mathrm{F_O} \times \mathrm{F_D}) + (\mathrm{t_N} \times \mathrm{F_O})]\}/1000 \\ &= \{(\mathrm{P_n} \times \mathrm{t_O}\}/1000 \quad [kWh] \end{aligned} \tag{5.8}$$

Where the following assumptions have been made:

- $F_c = 1$ since there old luminaires weren't dimmable
- $F_D = 1$ since there was no daylight harvesting.
- $(t_D+t_N) \times F_o = t_o$= operating hours

In conclusion the needed data needed to measure the energy consumption before the retrofit are P_n and t_o:

- P_n of each room has been calculated as $P_n=4\times P_i$. P_i of old luminaires has been measured in the laboratory.
- t_o has been assumed based on user's occupancy survey. Questions have been asked about occupancy pattern and usage of artificial lights if daylight was present.

Post-retrofit conditions

The Lighting Energy Requirements Calculated Method of European standard EN 15193 has been applied to calculate the energy consumption over one year.

LED luminaires without dimming

In the rooms where no active dimming has been installed there is no automatic controls and no emergency lights, so:

$$W_{\mathrm{t}} = W_{\mathrm{L,t}} = \sum \{(\mathrm{P_n} \times \mathrm{F_c}) \times [(\mathrm{t_D} \times \mathrm{F_O} \times \mathrm{F_D}) + (\mathrm{t_N} \times \mathrm{F_O})]\}/1000$$
$$= \{(\mathrm{P_n} \times \mathrm{t_O}\}/1000 \quad [kWh] \qquad (5.9)$$

Where the following assumptions have been made:

- $F_c = 1$ since there old luminaires weren't dimmable
- $F_D = 1$ since there was no daylight harvesting.
- $(t_D+t_N)\times F_o = t_o$= operating hours

In conclusion the needed data to measure the energy consumption in the case of LED luminaire without dimming controls are P_n and t_o:

- P_n of each room has been calculated as $P_n=4\times P_i$. P_i of the new luminaires has been measured in the laboratory.
- t_o has been assumed based on user's occupancy survey and on the measurements of energy consumption of the first three months.

LED luminaires with active dimming

In the rooms where active dimming system has been installed there is automatic occupancy and daylight controls but no emergency lights, so:

$$W_{\mathrm{t}} = W_{\mathrm{L,t}} + W_{\mathrm{P,t}} = \frac{\{\Sigma\{\mathrm{P_n}\times[(\mathrm{t_D}\times\mathrm{F_O}\times\mathrm{F_D})+(\mathrm{t_N}\times\mathrm{F_O})]\}+\Sigma\{\mathrm{P_{pc}}\times[(\mathrm{t_y}-(\mathrm{t_D}+\mathrm{t_N})]\}\}}{1000} \; [kWh] \qquad (5.10)$$

Where these assumptions have been made:

- P_n = total installed lighting power in the room or zone.
  $P_n = \Sigma P_i$ [W]
- F_c =constant illuminance factor
  F_c =1 since the luminaires outputs is considered constant over their lifetime,
- F_o = occupancy dependency factor
  $F_o = F_{OC} + 0{,}2 - F_A$. The standard gives benchmarks values for F_{OC} and F_A. F_{OC}=0,95 for auto on/dimmed systems with automatic presence and absence

detection. F_A=0,3 for office with 2-6 persons. Therefore F_o=0,85 has been used.

- F_D = daylight dependency factor. It depends on the geometry of the room and of the windows, on the location of the building, on the orientation of the windows and on the surrounding areas.
- t_D = operating hours during the daylight time, measured in hours
- t_N = operating hours during the non-daylight time, measured in hours
- P_{pc} = input power of all control systems in luminaires in the room when the lamps are not operating, measured in watts
- t_y = standard year time, 8 760 h

In conclusion the needed data to measure the energy consumption in the case of LED luminaire with active dimming controls are P_n, t_D, t_N, F_{OC}, F_A, F_D and P_{pc}:

- P_n of each room has been calculated as P_n=4×P_i. P_i of the new luminaires has been measured in the laboratory.
- t_D and tN have been assumed based on user's occupancy survey, working days calendar and daylight hours/month at Helsinki latitude.
- F_{OC}, F_A values have been assumed based on standards benchmark values.
- F_D depends on window geometrics, building position and surrounding. Room measurements have been taken during initial visit survey. Afterwards the rooms have been modelled in Dialux and F_D has been computed by the software.
- P_{pc} of luminaires has been measured in the lab.

***Table 7** - Needed data for energy consumption and efficiency assessment*

Needed data for energy consumption and efficiency assessment	**Methods**
Luminous flux (F)	Measured in the laboratory
A	Measured in the room
P_n	Measured in the laboratory
t_o	User survey Assumptions
t_D, t_N	User survey Daylight astronomic data
F_{OC}, F_A	Benchmark values
F_D	Room measurements Dialux simulation
P_{pc}	Measured in the laboratory

5.3.2 Light environment

The European standard EN 12464-1 “Lighting of work places – Indoor work places” (20) gives minimum requirements that workplace light environment need to meet in order for the users to fulfil their visual tasks in an efficient, accurate and safe way. These requirements are expressed in terms of minimum required average illuminance per task, maximum URG, minimum uniformity and minimum required Ra. However lighting quality is much more than meeting these requirements. As fully explained in Chapter 3.5, it is difficult to describe the complexity of a luminous environment only with photometric measurements. Many factors that contribute to lighting quality depends on the users’ visual system and subjective preference and the investigation of users’ experience and opinions is necessary to discover local or transient unpleasant occurrences (e.g. glare, flickers, erratic response of the automatic control system, etc.).

The increment in lighting quality assessment has been divided into two parts:

- Verify that the lighting system meet the minimum requirement of the standard
- Monitoring of other factors that can cause visual discomfort and influence lighting quality

Standard minimum requirements

To verify if the lighting environment meet the standard requirement the following data are needed:

- *Average Illuminance*

To compute the average illuminance the value of illuminance in many points of the work pane is needed. Spot illuminance has been directly measured in the room before and after the retrofit. Attention has been paid to measure spot illuminance in the same points both times. Moreover a simulated value of E_m has been computed modelling the rooms in Dialux.

- *Illuminance uniformity*

Uniformity U_O is the ratio between the lowest (E_{min}) and the mean illuminance level ($\bar{E}$) in the task area. To compute U_O measured and simulated values of spot illuminance have been used.

- *URG*

UGR (Unified Glare Rating) is a method to measure the probability of psychological glare. UGR calculations involve the luminance and size of the glare source, the luminance of the background and the position of the glare source relative to the line of sight. UGR is defined as:

$$\mathrm{UGR} = 8\log\left[\frac{0{,}25}{\mathrm{L}_\delta}\sum\frac{\mathrm{L}^2\Omega}{\mathrm{p}^2}\right] \qquad (5.11)$$

However both in the pre and post retrofit analysis UGR has not been analytically compute. UGR values have been computed both with Photolux and Dialux simulation software.

- *Colour rendering Index value*

The colour rendering index (CRI) is a quantitative measure of the ability of a light source to faithfully reveal the colours of various objects in comparison with an ideal or natural light source. The Ra values of both old and new light sources have been measured in the laboratory.

Other factors

- *illuminance distribution*

Illuminance distribution pattern is an important factor in lighting quality. Analyzing the illuminance distribution it is possible to check if the lighting system matches the task area; if it can create distraction, drawing the user attention away from the task area; it shows if some light is wasted where it is not needed and it gives a more complete description of illuminance uniformity on the work area. Illuminance distribution has been simulated with Dialux.

- *luminance distribution*

High luminance ratio within the task area can cause glare and eyestrain. Especially luminance ratio between computer screen and immediate and remote surroundings should be studied. Maximum luminance ratios of 1:3 in the immediate and 1:10 in the remote surroundings should be respected. Spot luminance values have been directly measured in the room. Luminance values distributions have been measured with HDR fisheye photographs and Photolux simulations.

- *light colour temperature*

Light colour influences the perception of the environment and can influence the mood of the users. The correlated colour temperature (CCT) of the light produced by both old and new luminaire has been measured in the laboratory. Moreover the CCT of the light in the room (influenced by the reflections on the room surfaces) has been measured. Users' opinion about light colour has been asked before and after the retrofit.

- *presence of veiling reflections, shadows and flickers.*

Veiling reflections, shadows and flickers are local and transient occurrences that are difficult to discover during the room measurements. Therefore users' experience and opinions have been investigated through questionnaires and oral interviews.

Table 8 - *Needed data for lighting quality assessment*

Needed data for lighting quality assessment	Methods
Spot illuminances	Directly measured in the room Dialux simulation
UGR	Dialux simulation Photolux simulation
CCT	Measured in the laboratory Directly measured in the room Users' survey
Ra	Measured in the laboratory
Spot luminance	Directly measured in the room
illuminance distribution	Dialux simulation
luminance distribution	Photolux simulation
presence of veiling reflections, shadows and flickers	Users' survey
NOTE: for Dialux simulation also these data were needed:	
Reflectance of surfaces	Measured in the room
Luminous intensity distribution of old luminaires	Measured in the laboratory
Luminous intensity distribution of new luminaires	Manufacturer webpage (41)

5.3.3 Cost analysis

A life cycle cost (LCC) analysis has been applied to calculate the cost of energy efficiency improvement of the lighting system.(42) In addition paid back time of the investment has been computed to check if there would be an economic return after the service time.

Life cycle costing

Life cycle costs (LCCs) analysis, in contrast to conventional cost accounting, takes into account the costs and the monetary flows occurring over the entire life cycle of the product. It includes costs as input and revenue as output. Depending on the scope and goal of the assessment, the LCC may be concentrate only on certain stages of the life cycle and ignore the rest (42).

In this case study LCC analysis is conducted from the point of view of the investor so it focuses on the use and maintenance stage, ignoring the manufacturing and disposal processes.

The LCC is the sum of investment cost (PC), the annual operating cost (OC) and the disposal cost (DC) discounted over the lifetime of the product. In this case disposal cost has not been considered since the exact price was difficult to assume and anyway, after the discounting, its value would have been negligible if compared to the investment cost and operating cost. PC is the sum of the cost of the new lighting system and the installation costs. OC have been calculated multiplying the expected annual consumption of the lighting system by the cost of electricity. For simplicity maintenance costs have not been considered.

LCC is calculated by the following equation:

$$LCC = PC + \left(\frac{1-(1+r)^{-n}}{r}\right) OC \tag{5.12}$$

Where OC has been discounted over life time by discount rate r. The discount rate in present value analysis takes into account not just the time value of money, but also the risk or uncertainty of future cash flows; the greater the uncertainty of future cash flows, the higher the discount rate. In LCC computation the real discount rate r_r has been used. The real rate of interest is the nominal rate r_n after the rate of inflation i has been removed. Inflation has to be removed from the discount rate since projected OC have been estimate without taking into account inflation. Since OC are expressed in real values, real discount rate has to be used. Real discount rate r_r is calculated as:

$$r_r = \frac{(r_n - i)}{(1+i)} \tag{5.13}$$

Annual savings (AS) have been computed as the difference between the annual running costs of the old and new lighting system:

$$AS = OC_o - OC_n \tag{5.14}$$

and these values have been used to compute the present value of the economical savings over the entire life time of the new lighting system.

$$PVec.savings = \left(\frac{1-(1+i)^{-n}}{i}\right) AS \tag{5.15}$$

The economical savings have been compared to the investments costs to assess if the investment had an economic return. If the return is present payback time PB will be calculated through cash flows analysis keeping into account the time value of the money.

Table 9 *- Needed data for cost analysis*

Needed data for cost analysis	**Sources and methods**
Price of the new lighting system (€)	Manufacturer's bill
Installation costs (€)	Installer's bill
Annual consumption (kWh/year)	From energy consumption analysis
Electricity price	Worst case of public users electricity tariffs found in (43)
Discounting rate	From literature review(42)

5.3.4 User satisfaction

Assessing the users' satisfaction before and after the retrofitting is validated instrument providing information about quality, quantity and distribution of light, appearance of the room, influence of the lighting on the work performance. The users' opinions are a reliable representation of the improvement or worsening of the light environment after the retrofit under different points of view. In this case users have been asked to grade the lighting conditions pre and post the retrofit from these points of view:

- Appearance of the lighting system
- Appearance of the room and of the lighting environment
- Amount of light
- Glare
- Colour temperature and naturalness
- Visibility and visual performance
- Lighting preference

5.4 Collecting data: Methods and instruments

5.4.1 Room measurements

Two room measuring session have been conducted: one before and one after the lighting retrofit. During these sessions the following instruments have been used:

- **LMT Pocket Lux 2 illuminance meter:** it has been used to measure spot illuminance and CCT. Illuminance has been measured in several points and particular attention had been paid to use the same measuring points in both the measuring session.
- **Nikon Coolpix 8400 calibrated digital camera with Fish-eye lens:** it has been used with a tripod to take photos of working stations at sight high under 13 different expositions. Before taking photos the camera image options have been set as described in Photolux manual. To cover the whole range of luminances of the room (1-100000 cd/m2) 13 exposure times have been chosen (4.8, 5.8,...,15.8 and 16.4), each exposure time corresponds to a combination of time of exposure (t) and aperture (F).
- **LS-100 luminance meter and white reference reflector:** it has been used to measure spot luminance and the reflectance of the surfaces. To measure the reflectance, both luminance of the surface and of the reference reflector have been measured from the same measuring point and angle. The reflectance has been measured as ration between the luminance of the surface and the reference reflector

  $$\rho = L_{surface}/L_{reference} \tag{5.16}$$
- **Measuring tape:** it has been used to measure inner length of the walls, height of the ceiling, height of the working pane, window dimensions including frames, position of the luminaires.

5.4.2 Laboratory measurements

In order to estimate the photometric and electrical performance of the old luminaire and to check the real performances of the new ones, they were measured in the laboratory facilities of Aalto University Lighting Unit.

Labshpere:

First measurement set-up consisted of Labshpere diode array spectrometer with 2-metre integrating sphere and a laptop PC with respective software for running the system. The set-up has been used to measure luminous flux, radiant power, colour temperature (CCT) and colour index of the tested light source.

Two old luminaires have been measured: one two-lamp slots troffer and one three-lamp slots troffer. Both lamps outputs have been measured after 30 min to allow the fluorescent lamps to warm up.

Three LED luminaire without dimming have been measured, each one has been measured three times: after two minutes, after 15 minutes and after 30 minutes the lamp was turned on, in order to analyze how the parameter changed with the warming up of the lamp. The same procedure has been applied to three LED luminaire with active dimming but these lamps have been measured twice: after two minutes, after 15 minutes. In the end LED luminaire performances have been considered as an average of the measured values.

Yokogawa WT130 digital power meter

It was used to monitor voltage and current during the measurement in the Labshpere. In addition it has been used to measure power consumption of the luminaires and power factor.

OxyTech T2 Goniophotometer

To simulate pre and post retrofit conditions in Dialux the light intensity and distribution of the luminaires is needed. The light distribution file of LED luminaire was given by the producer, while the light distribution of the old luminaires had to be measure. Therefore the goniophotometer has been used to measure the light emitted by the luminaires from 37 gamma angles and 24 C-planes. The chosen distance between C-planes was 15° while the distance between gamma angles was 5°. The measurements output are luminous intensities tables and light distribution curves in an .LDT file. At a later stage these files have been edited, adding the luminous flux of the luminaires measured in the Labshpere and the geometrical dimensions of the luminaire and of the luminous area. Then the files have been imported in Dialux for the simulation of the room conditions.

5.4.3 Simulations

Photolux

Photolux is a photometric measurement system, consisting in a compound of a processing software and a calibrated digital camera provided with an Fish-eye lens.

The camera is calibrated in luminance. Photolux software integrates the calibrated results and produces HDR luminance maps out of the camera images. Luminances maps cover a range of luminances from 0.1cd / m^2 to 500 000 cd / m^2 with a 180° field of vision and curves of calibration.(44) The software is used to make luminance statistical analyses on the complete map and calculate average luminance of the room and the indices of comfort UGR (EN 12464-1).

Dialux

Dialux is a free lighting calculation software that uses a radiosity method for the computation of light distribution (45). A 3D model of the rooms has been drawn and the software was given the information about the building location and exposure and the .LDT files of both old and new luminaires. Therefore it has been possible to use Dialux for day-lighting factors calculations according to En15193, to simulate both pre and post retrofit interior scenes, study the illuminance levels and distribution and compute UGR value for usual working positions.

5.4.4 User surveys

General preliminary questionnaire

The preliminary questionnaire purpose was to obtain a general understanding of the luminous environment as perceived by the occupants as well as subjects' preferences and usage patterns. The questionnaire used by Hygge and Löfberg in (46) was used as reference. The questionnaire was not supposed to be used for statistical analysis since the subjects were not enough, so the type of question asked didn't have to fulfil statistical analysis requirements. The aim was to record usage pattern of each room, get to know the room users and understand the general condition of the rooms. The information collected has been used to write the second user survey questionnaire. The questions of the general preliminary questionnaire could be divided into five groups: users' usage pattern and preferences, quality of the environment, quality and quantity of light, distribution, and general appearance of the environment. The questions involved both daylight (e.g. glare, sun patches, curtains, etc.) and electric lighting issues (e.g. uniformity, use of control systems, etc.).The general questionnaire combined closed and open questions. The full text of the questionnaire can be found in Appendix 1

Pre and post retrofit user survey

To evaluate users' opinion and satisfaction and to asset the improvement or worsening of the light environment, room occupants had to fill in the same users' survey twice: once before and once after the retrofitting. This questionnaire could be filled in less than five minutes and it consisted in yes/no questions as well as grading scales. The questions layout and structure have been studied to avoid to influence the users' answers and to have consistent results. The questions were about appearance of the lighting system, appearance of the room and of the lighting environment, amount of light, glare, colour temperature and naturalness, visibility and visual performance and lighting preference. The full text of the questionnaire can be found in Appendix 2. The questionnaire was structured in a way that allowed the data treatment in a simple Excel sheet. The statistical analysis of the results has not been performed since the users sample was not enough numerous. The data analysis consists in the digitalization of the questions for basic elaborations such as the average score for the questions and the comparison of the results pre and post retrofit.

6 . Results

6.1 Energy efficiency

6.1.1 Usage pattern

To compute the energy savings achieved by the lighting retrofit some assumption had to be made about usage patterns of the space. First of all through the general questionnaire users declared to work in the rooms for an average of 6-8 hours a day. Considering that two people were working in each office, rooms have been considered occupied for 8 hours a day by at least one employee.

Second, average daylight time usage t_D and non-daylight time usage t_N have been calculated based on monthly average daylight hours per day in Helsinki, as shown in Table 10 . The monthly average daylight hours have been decreased by two hours considering the hour after the sunrise and the hour before the sunset as non-daylight time hours. These values have been implemented in Dialux software simulation for the energy efficiency evaluation of the room. The numbers of workdays/month take into account weekends and national holidays.

Table 10 *- Daylight and non-daylight time computation*

	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**
Average Sunlight Hours/ Day	01:05	02:13	04:21	06:08	08:42	09:48
(Average Daylight Hours,/ Day)-2hours	5h 47m	7h 05m	9h 47m	12h 37m	15h 14m	16h 46m
Workdays (8hours a day from 8.00 to 16.00)	16	20	22	20	19	22
Average tD per day	5,47	7,05	8,00	8,00	8,00	8,00
tD month	92,32	141,40	176,00	160,00	152,00	176,00
Average tN day	2,13	0,55	0,00	0,00	0,00	0,00
tN month	35,28	18,20	0,00	0,00	0,00	0,00

	Jul	Aug	Sep	Oct	Nov	Dec
Average Sunlight Hours/ Day	09:30	08:05	05:04	02:27	01:00	00:34
(Average Daylight Hours/ Day)-2hours	16h03m	13h41m	10h53m	8h03m	5h27m	03h59m
Workdays (8hours a day from 8.00 to 16.00)	20	18	22	22	21	18
Average t_D per day	8,00	8,00	8,00	8,00	5,27	3,59
t_D month	160,00	144,00	176,00	176,00	114,27	71,42
Average t_N day	0,00	0,00	0,00	0,00	2,33	4,01
t_N month	0,00	0,00	0,00	0,00	53,33	72,18

These calculations resulted in 240 workdays/years; the 1920 hours/year in which rooms are occupied are divided in an annual tD of 1740 hours and an annual TN of 180 hours. Users were asked if they are used to switch off the light if daylight is enough to work with. In four of the rooms occupants used to do it only in summer. In the other two rooms occupants prefer to work with the blind shut during the whole year time. Computing with Dialux daylight availably in Helsinki during summer, this usage behaviour has been modelled assuming that for 20% of summer days the lights were turned down.

In addition the four old troffers in each room were divided into two manual control groups that could be separately switched on and off. Users were asked if they used to switch on both groups or only one. Moreover they were asked whether they were using additional desktop lamps or not. In two rooms before the retrofit both of the occupants used to use desktop lamps. After the retrofit users declares that desktop lamps are not needed anymore. Desktop lamps have been considered to consume 30W each. Table shows how usage pattern has been modelled for each room.

Table 11 *- Rooms Usage Patterns*

Room nr.:	i336	i337	i338	i433	i434	i435
Hours A Day	8	8	8	8	8	8
Nr.Of Luminaires Used Pre-retrofit	2	2	4	4	4	4
Nr.Of Luminaires Used Post-retrofit	4	4	4	4	4	4
Desktop Lamp Pre-retrofit (W)	0	0	0	60	60	0
Desktop Lamp Post-retrofit (W)	0	0	0	0	0	0
Only Daylight In Summer	0,2	0	0,2	0,2	0,2	0
Common Data:						
Working Days	240					
Summer Days	121					
Rooms area (m^2)	19,78					

6.1.2 Luminaires performance

To know the total installed power, luminaires performance has been measured in the Lab thanks to Labsphere system and digital power meter. The results are shown in Table 12

***Table 12** - Luminaires performance*

	Dimming	Power	Flux	CCT	Ra	Efficacy
3 lamp slots troffer	No	49 W	1831 lm	3027 K	85	**37 lm/W**
2 lamp slots troffer	No	49 W	1983 lm	2986 K	85	**41 lm/W**
AIL1543F LED40W/840	No	40 W	2755 lm	4111 K	84	**70 lm/W**
AIL1543F LED35W/840	yes	35 W	3378 lm	4094 K	84	**96 lm/W**

Old luminaires were consuming 49 W each while new LED luminaires wattages are 35W and 40W, measurements of the new luminaires matched the values declared in the products datasheets. Increments in the luminous flux output as well as decrements in the lamps wattages lead to a luminous efficacy of the new luminaires that is around the double of the old luminaires one.

6.1.3 Annual energy consumption per room and energy savings

Thanks to the usage pattern model, the lighting system operating hours of each room has been computed. Total installed power takes into account for luminaire per room plus additional desktop lamps if present. Annual running cost have been computed considering Finnish electricity cost equal to 12 c€/kWh (43).

__Table 13__ - Energy Savings

Room nr.:	i336	i337	i338	i433	i434	i435
PRERETROFIT						
operating hours/ year	1726,4	1920	1726,4	1726,4	1726,4	1920
total power [kW]	0,098	0,098	0,196	0,256	0,256	0,196
annual energy consumption [kWh]	169,2	188,2	338,4	491,5	442,0	376,3
annual running cost[€]	20	23	41	53	53	45
LENI [kWh/(m2 year)]	8,55	9,51	17,11	22,34	22,34	19,03
POST RETROFIT						
equivalent hours of max power/ year	1019,1*	1920	reference	1726,4	1019,1*	reference
total power [kW]	0,14	0,16		0,16	0,14	
annual energy consumption [kWh]	142,7	307,2		276,3	142,7	
annual running cost[€]	17	37		33	17	
LENI[kWh/(m2 year)]	7,21	15,53		13,96	7,21	
ANALYSIS						
energy savings [kWh/years]	27	-119		166	299	
energy savings [%]	16	-63		38	68	
energy savings in eq. days of max power	17	-76		106	191	
*these values have been computed in Dialux						

As described in ***Table 13***, energy savings have been achieved in three of the four rooms that have been retrofitted. The magnitude of the savings depends on the amount of energy used before the retrofitting and on the installation of lighting controls. In the rooms where desktop lamps were used and all four the old troffers were operating 8 hours a day energy savings are important (38% and 68%). In rooms i336 and i337 only two of the four old troffers were used, while after the retrofitting all four lamps are used. Therefore the total power used for lighting has been increased by the retrofit. However, according to the Dialux simulation of daylight availability, the installation of active control system in room i336 is supposed to reduce consistently the operating hours of the lighting system and some savings are anyhow achieved (16%). In the last row of ***Table 13***, savings are expressed in terms of reduction of the operating days to be applied to the old lighting system to achieve the same energy savings, for example in room 434 the energy savings due to the retrofit have been 299 kWh/years, that is the same amount of energy that could be saved if occupants didn´t use the old artificial lighting system for 191 working days. LENI values have been computed for each room in pre and post retrofit condition. In **Table 14** LENI limiting values given by EN 15193 are presented. LENI values of all the rooms both before and after the retrofit respect standard limiting values.

Table 14 – LENI limiting values from (17)

Quality class	**No cte illuminance**		**Cte illuminance**	
	LENI Limiting value		LENI Limiting value	
	manual	auto	manual	auto
*	34,9	27,0	31,9	24,8
**	44,9	34,4	40,9	31,4
***	54,9	41,8	49,9	38,1

6.1.4 Metered weekly energy consumption

After the retrofit kWh meters have been installed in room 433 and 434, so energy consumption has been metered weekly for three months. Energy consumption of room 435, that has not been retrofitted, has been used as reference for the analysis of the energy savings. Energy consumption of room 435 has not been metered but computed assuming daily operating time of the luminaires equal to 8 hours. It´s important to remember that the wattage installed in the rooms is not the same, in room 435 the total installed power is 196 W, in room 433 is 160W and in room 434 is 140W. Table 15 shows the metered values, then plotted in ***Figure 25*** and Figure 26. Since the wattage is different the savings due to the implementation of active dimming controls are studied in terms of equivalent hours of maximum power. In other words to understand the benefits due only to the control system and not to the more efficient luminaires, the analysis cannot be based on the consumed kWh but it is studied in terms of ratio between the metered kWh and the installed power. Computing the average between week 7 and week 13 (when usage pattern stabilised after Christmas holidays) it resulted that in room 433 lighting system is used 7 hours and 57 minutes per working day while in room 434 is used 5 hours and 35 minutes. This means that a lighting system of a certain wattage and equipped with dimming control on average consumes 30% less than the same system without dimming control. However these analyses are based on the metered energy consumption of winter month when the day harvesting system had not been exploit. If these values were used as starting base to forecast the annual energy consumption it would result in 188 kWh/year, 31% more than what computed by the simulation in Dialux. This is because software simulation took into account the energy savings due to daylight harvesting during summer period. To assess if the software simulation is reliable a longer metering period is needed.

Table 15 - Metered energy consumption

	Total kWh consumed			Weekly kWh			Equivalent hours of max power		
week	room435 196 W	room433 160W	room434 140W	room435 196 W	room433 160W	room434 140W	room435 196 W	room433 160W	room434 140W
0	0	0	0						
1	7,84	4,8	1,7	7,84	4,8	1,7	8	6	2,43
2	15,68	10	7,1	7,84	5,2	5,4	8	6,5	7,71
3	23,52	14,8	11,2	7,84	4,8	4,1	8	6	5,86
4	24,02	15	11,8	0,5	0,2	0,6	0,5	0,25	0,86
5	24,52	15,4	12,9	0,5	0,4	1,1	0,5	0,5	1,57
6	32,36	20	15,3	7,84	4,6	2,4	8	5,75	3,43
7	40,2	26,4	19,1	7,84	6,4	3,8	8	8	5,43
8	48,04	32,6	21,7	7,84	6,2	2,6	8	7,75	3,71
9	55,88	39	26,3	7,84	6,4	4,6	8	8	6,57
10	63,72	46	30,3	7,84	7	4	8	8,75	5,71
11	71,56	52,8	34,2	7,84	6,8	3,9	8	8,5	5,57
12	79,4	58,6	39	7,84	5,8	4,8	8	7,25	6,86
13	87,24	64,6	42,7	7,84	6	3,7	8	7,5	5,29

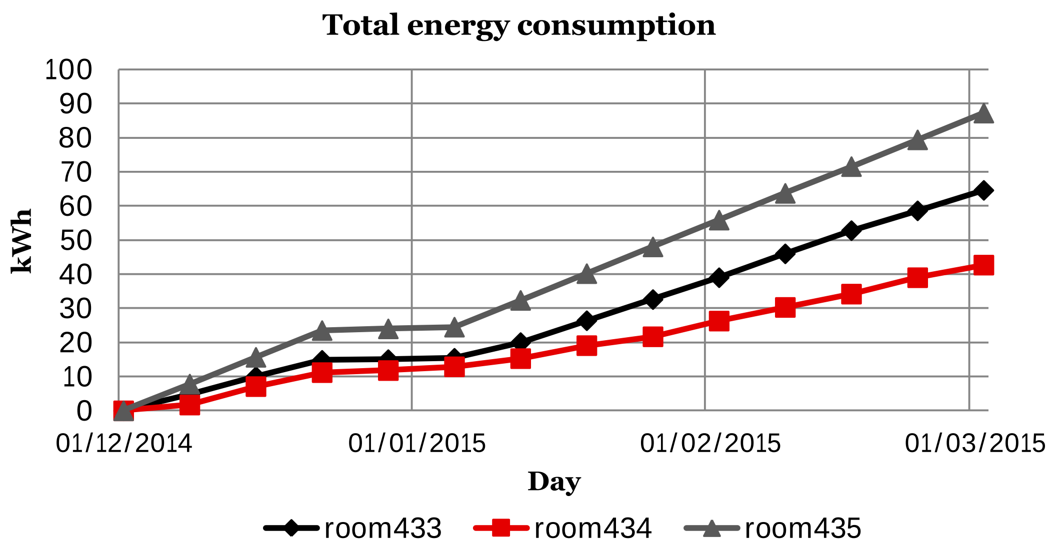

***Figure 25**- Total energy consumption of the new lighting system in rooms 433 and 434, room 435 is used as reference*

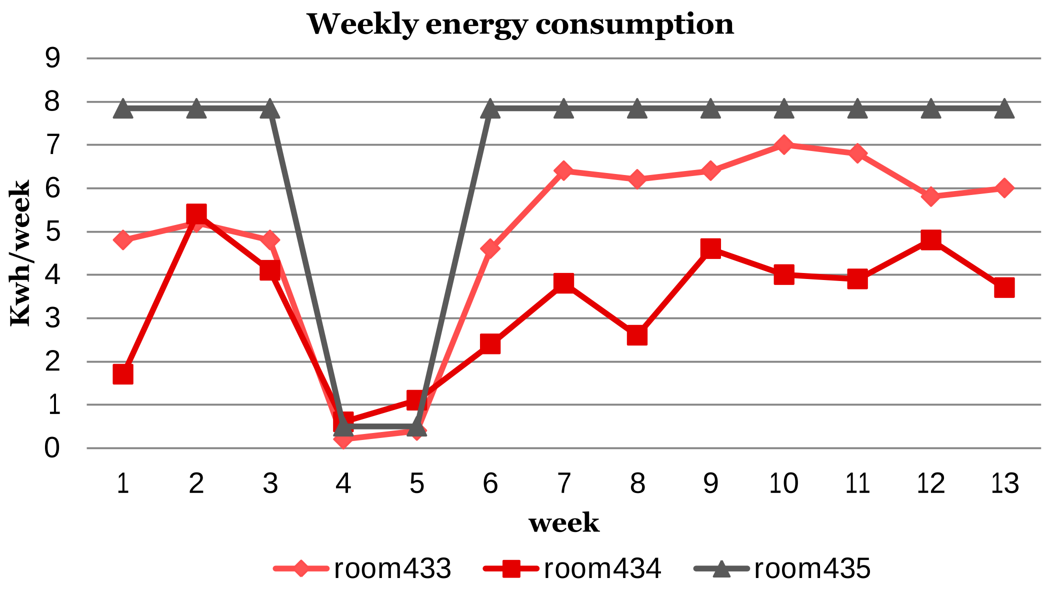

Figure 26 - *Weekly energy consumption of the new lighting system in rooms 433 and 434, room 435 is used as reference*

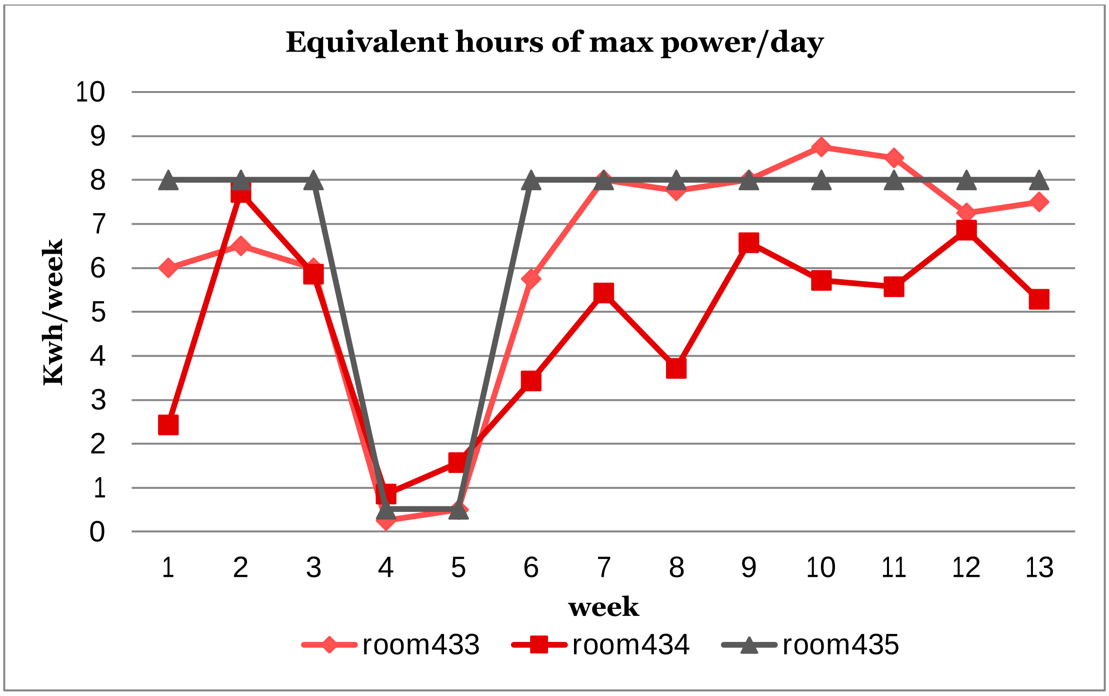

Figure 27 - *Equivalent hours of maximum power in rooms 433, 434 and 435*

6.2 Light environment

6.2.1 Illuminance

Illuminance on the working plane is the key factor determining the acceptability of the lighting for visual task performance in most environments. Whilst it is generally agreed that the visual quality of a space cannot be fully described in terms of horizontal illuminance, this is the most commonly used metric for evaluating the adequacy of illumination levels in a space. In addition to illuminance sufficiency for visual tasks, other concerns for sufficient circadian stimulus levels, or excessive daylight levels leading to glare conditions or overheating, can also be assessed or inferred. The current lighting recommendations EN-12464-1 (20) prescribes average illuminance of 500 lx for visual tasks like writing, typing, reading, data processing. Moreover illuminance uniformity has been described as highly desirable, especially across the working surface. Excessive variation in horizontal illuminance may contribute to transient adaptation problems and distraction. Therefore, lighting standards often contain recommendations regarding the uniformity of illuminance on the work plane. EN-12464-1 prescribes for the types of visual task performed in these rooms uniformity of illuminance of at least 0,6. Table 16 illustrates the level of illuminance measured and simulated in every room in pre- and post-retrofitting lighting conditions. Values coloured in red are the ones that don´t meet lighting recommendations of EN-12464-1. Pre-retrofit lighting conditions didn´t meet the standard in every room or in term of average illuminance, or in terms of uniformity or both depending on the room. After the retrofit standard minimum values are always meet. Figure 3 and ***Figure 29*** shows Dialux simulations for pre- and post-retrofit lighting conditions

***Table 16** - illuminance levels before and after the retrofit*

	i336 pre	i336 post	i337 pre	i337 post	i338 pre		
illuminance:							
average	184,4	570	241,75	545	213,15		
maximum	245,2	603	335,8	630	270		
minimum	123,6	537	147,7	460	156,3		
uniformity	0,50	0,89	0,44	0,73	0,58		
	i433 pre	i433 post	i434 pre	i434 post	i435 pre	simulation pre	simulation post
Illuminance:							
average	562,4	557	363,9	537	306,5	326,5	529
maximum	832,3	612	412,2	586	343	423	655
minimum	292,5	502	315,6	488	270	230	403
uniformity	0,35	0,82	0,77	0,83	0,79	0,54	0,62

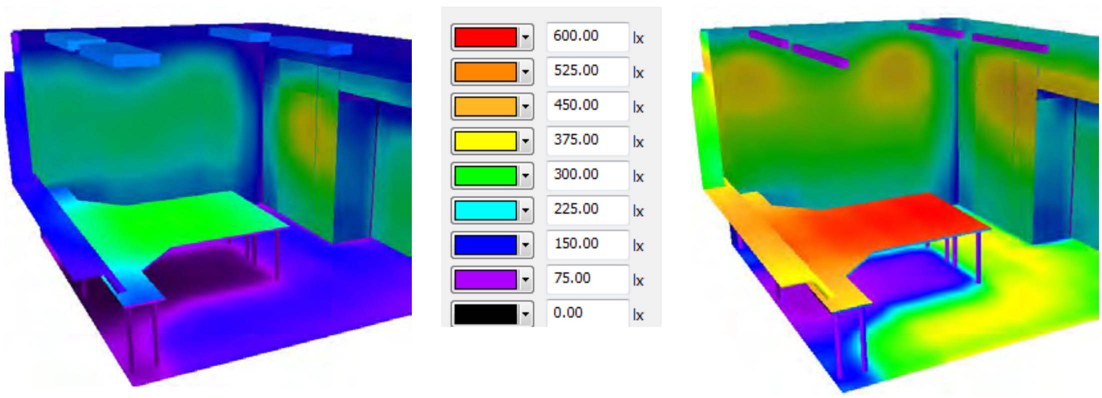

***Figure 28**-Dialux simulations. False colour rendering showing illuminance distribution*

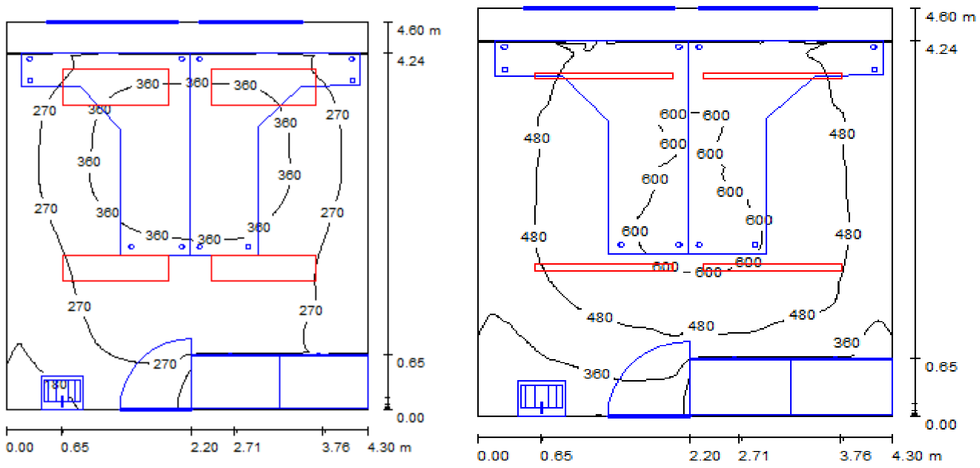

***Figure 29**-Illuminance distribution simulations: pre- and post- retrofit*

6.2.2 Glare and luminance levels

Avoiding disability and discomfort glare is essential to guarantee lighting quality in workplaces. Unified Glare Rating UGR has been evaluated in every room thanks to Photolux system for both pre and post lighting conditions. UGR for all the rooms in pre-retrofit conditions was less than 10. UGR values after the retrofitting were increased, for all the rooms were between 16 and 18. The increasing of the values is due mainly to two reasons: first the new luminaires have a greater luminous flux output and second LED sources have a smaller emitting area. Nevertheless maximum UGR level prescribed by the EN-12464-1 is 19 and it has been respected also in post-retrofitting conditions. Moreover occupants have been asked if they perceived any glare in the room before and after the retrofit and the answers were negative in both cases. ***Figure 30*** shows the increment of luminance level in the room due to the retrofit. The importance of considering luminance distribution and contrast in the visual environment comes from the fact that the human eye, in spite of its capacity to sustain great variations in luminance, cannot adapt to large luminance variations simultaneously.

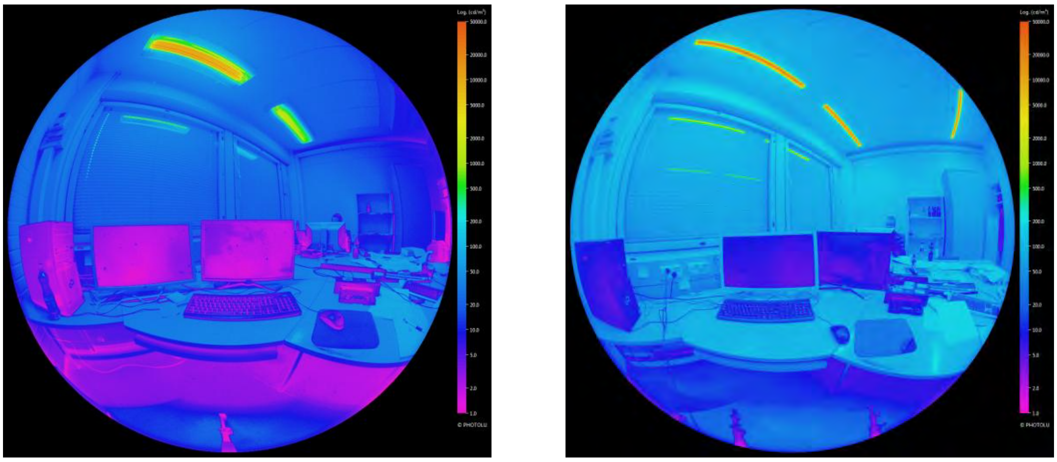

Figure 30 *– Photolux luminance map of one of the workstation before and after the retrofit*

6.2.3 CCT and Colour Rendering

As stated in the standard EN-12464-1, the choice of the apparent colour of a lamp is a matter of psychology, aesthetics and of what is considered to be natural. On the other hand the colour rendering of a light source should be adequate for the task being performed. According to standard EN-12464-1, it is important for visual performance and the feeling of comfort and wellbeing, that colour in the environment, of objects and of human skin are rendered naturally, correctly and in a way that makes people look attractive and healthy (20). In order to provide an objective indication of the colour rendering properties of a light source, the general colour rendering index CRI or Ra has been introduced and EN-12464-1 set its lower limit value at 80.

To know CCT and Ra, luminaires have been measured in the Lab thanks to Labsphere diode array spectrometer. As ***Table 17*** shows, old luminaires had a warm colour temperature while new LED luminaires have a cooler appearance. Room occupants have been asked to rate the colour temperature of the luminaires deciding if the colour of the light in the room could be defined really cold, cold, slightly cold, neutral, slightly warm, warm or really warm. In both cases almost all the occupants defined neutral the colour of the light. Moreover users were also asked to rate the colour naturalness of their hand and of the furniture of the room. Even if colour rendering index of Led luminaires is slightly smaller than the one of the fluorescent lamps, users perceived greater colour naturalness in post-retrofit conditions than before retrofit. This can be due to the fact that illuminance levels before the retrofit were really low. Finally it is important to remember that the survey sample was not enough numerous so users´ survey results are more indicative than generally reliable.

Table 17 *–Colour features of the luminaires*

	CCT	Ra
3 lamp slots troffer	3027 K	84,92 Ra
2 lamp slots troffer	2986 K	84,92 Ra
AIL1543F LED40W/840	4111 K	83,91 Ra
AIL1543F LED35W/840	4094 K	83,96 Ra

6.2.4 Presence of veiling reflections, shadows and flickers.

Users' experience and opinions have been investigated through questionnaires and oral interviews in order to discover presence of veiling reflections, shadows and flickers. Both in pre and post retrofit conditions occupants haven´t ever perceived any.

6.3 Cost analysis and economical savings

A life cycle cost (LCC) analysis has been applied to calculate the cost of energy efficiency improvement of the lighting system in a room over its entire life span. In addiction annual savings have been computed to check if there would be an economic return of the investment.

Collected and assumed data used for cost analysis are summarised in Table 18.

Table 18 *–Data used for cost analysis*

Data	**Unit**	**Value**
electricity cost	€/kWh	0,12
working hours a year dimming	hours/year	1019
working hours a year no dimming	hours/year	1726
nominal discounting rate	%	6
inflation	%	3
real discounting rate	%	2,91
old luminaire:		
power consumption one room worst case	kWh	442
running cost worst case	€/year	53
new luminaires		
LED module expected lifetime	Hours	50000
expected life dimming	Years	49
expected life no dimming	Years	29
power consumption dimming	kW	0,14
power consumption no diming	kW	0,16
operating cost dimming	€/years	17
operating cost no dimming	€/years	33
price of 4 new luminaires dimming	€	840
price of 4 new luminaires no dimming	€	760
price of installation per room	€	600

According to the manufacturer LED module expected lifetime is 50000 hours, taking into account the expected operating hours of the lighting system using dimming control it means that the luminaires is expected to work for 49 years, while the lighting system without dimming control is expected to work for 29 years. Nevertheless the chances that the new lighting systems will be used for so long are few since indoor lighting system are often replaced, lighting system can break before the expected lifespan ends especially if electronics component are present or, even if still operating, room purpose can change. LCC indicates what are the costs generated by the lighting system during the whole life span so an evaluation of the system life span is needed. LCC analysis has been conducted for three different scenarios: 10, 15 and 20 years of operation. The two retrofitting options are then compared on the basis of the costs generated. Payback time instead is the same for all scenarios since depends on the running costs and not on the expected lifespan. Methods and formula used for the cost analysis are described in Chapter 5.3.3. Results of the cost analysis are presented in Table 19.

Table 19 - *Cost analysis*

Scenario 1		
cost analysis dimming		
Life time	years	10
investment cost	€	1440
annual savings	€/year	35,9
total savings after 10 years	€	359,2
present value of savings	€	307,7
operating costs	€/year	17,1
Present value of 10 years operating costs	€	146,6
LCC	€	1.586,6
simple payback	years	40
cost analysis no dimming		
Life time	years	10
investment cost	€	1360
annual savings	€/year	19,9
total savings after 10 years	€	199
present value of savings	€	104
operating costs	€	33
Present value of 10 years operating costs	€	284
LCC	€	1.644
simple payback	years	68
Scenario 2		
cost analysis dimming		
Life time	years	15
total savings after 15 years	€	539
present value of savings	€	432
Present value of 15 years operating costs	€	206
LCC	€	1.646
cost analysis no dimming		
Life time	years	15
total savings after 15 years	€	299
present value of savings	€	122
Present value of 15 years operating costs	€	398
LCC	€	1.758

Scenario 3		
cost analysis dimming		
Life time	years	20
total savings after 20 years	€	718
present value of savings	€	539
Present value of 20 years operating costs	€	206
LCC	€	1.697
cost analysis no dimming		
Life time	years	20
total savings after 20 years	€	398
present value of savings	€	132
Present value of 20 years operating costs	€	497
LCC	€	1.857

Table 19 clearly shows that there is not a return of investments: investment costs are high and, since the Finnish electricity price is low, the annual savings on the operating cost cannot lead to a short payback time. However the cost analysis shows that even if the investment cost of the lighting system with control system is higher than the one without dimming control, its LCC is lower even in the case of a “short” (10 years) life time.

6.4 User satisfaction

6.4.1 Occupants

Altogether 11 room occupants participated in general questionnaire, 7 of them were male and 4 female. Aged varied from under 30 (5 occupants), between 30 and 39 (2 occupants), between 50 and 59 (2 occupants) and over 60 (2 occupants). Three of the occupants didn't participate to the pre-retrofit user survey. Only 5 occupants participate to the post-retrofit users' survey even if the occupants of the retrofitted rooms are 7.

6.4.2 Surveys

Change in users' satisfaction due to the retrofit is evaluated by comparing the average scored of every question of the two questionnaires. It has been evaluated the appearance of the lighting system, appearance of the room and of the lighting environment, amount of light, colour naturalness, visibility and visual performance. Full text of the survey can be found in Appendix 2.
Some of the questions required to grade lighting parameters from 1 to 7 where 1 indicates “totally disagree” and 7 indicate “totally agree”. Answers to these questions can be find in Table 20.

Table 20 *– User surveys results*

	Pre-retrofit									Post-retrofit				
user:	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**1**	**2**	**3**	**4**	**5**
environment:														
pleasant	5	6	4	6	5	6	5	5	5	6	7	7	7	6
comfortable	5	6	3	6	4	6	3	5	5	6	7	7	7	6
stimulating	5	5	3	6	4	6	4	4	4	6	7	4	6	4
visual scene:														
colourful	4	5	3	3	3	7	4	5	6	6	6	4	6	4
bright	5	5	3	5	3	5	6	4	4	6	7	6	7	5
uniform	6	6	2	3	3	7	7	4	6	7	7	6	7	5
visual performance	6	7	6	6	6	7	6	5	5	7	7	7	7	7
visual needs	6	3	6	6	5	6	2	5	5	7	7	7	6	7
colour naturalness														
hand	4	6	6	5	6	6	7	6	5	6	6	7	7	5
furniture	4	6	6	5	6	6	7	6	7	7	6	7	7	5
lighting preference	6	5	3	4	6	4	4	5	5	7	7	7	7	7

The results average has been computed for each question. Comparison of the results is presented in

Figure 31

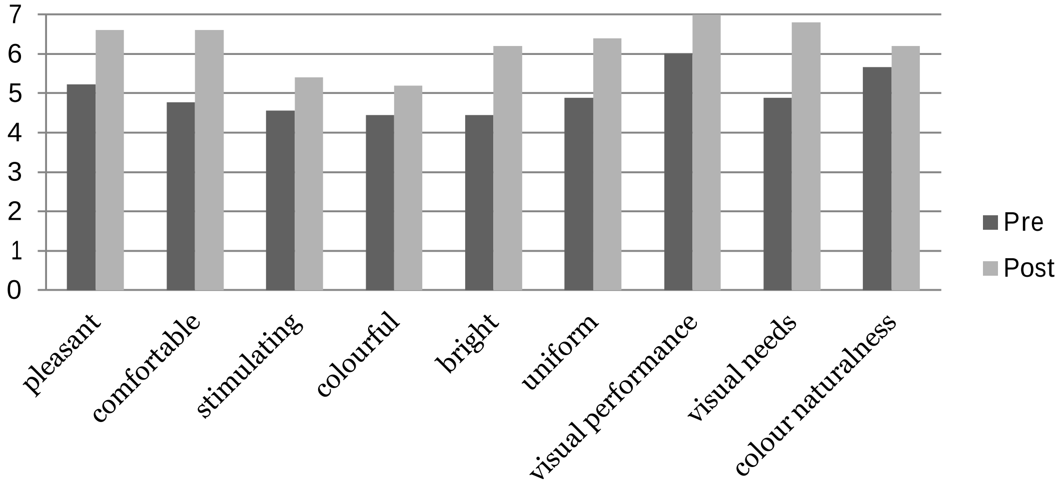

Figure 31 *– Users answers analysis*

Some of the questions required to grade lighting parameters from -3 to +3. Answers to these questions can be find in Table 21.

***Table 21** – User surveys results*

	pre-retrofit									post-retrofit				
user:	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**1**	**2**	**3**	**4**	**5**
amount of light:														
too low-3/ too high+3	0	0	0	+1	0	+2	0	0	-1	0	0	+2	0	0
colour temperature														
really cold-3/ really warm+3	+2	+1	0	-1	+1	+2	0	+2	+1	+1	+1	-2	+1	0
glare														
Yes/no	no	no	no	no	no	no	no	no	no	no	no	no	no	no

Users' surveys corroborate the result that lighting quality has been improved by the lighting retrofit.

6.5 Conclusions

In the rooms where four old luminaire and desktop lamp were used new lighting system brought great energy saving. Energy savings due to new luminaires without dimming are 38% of the pre-retrofit power consumption while the new luminaires with active dimming brought 68% of savings.

In the rooms where only two of the four old luminaire were used, the use of the new lighting without control increased the energy consumption by 63% while the new luminaires with active dimming allowed anyhow some savings equal to 16% the pre-retrofit power consumption.

The greater savings given by the presence of active dimming are due to the fact that the control systems reduce the average daily equivalent hours of maximum power of the lighting system operation by 30%: from 7 hours and 57 minutes to 5 hours and 35 minutes.

Energy savings are not translated in economical savings. In fact, since the investment cost are high and electricity is cheap, payback time is really high (more than 40 years) and return of investment is not possible.

Nevertheless, LCC analysis shows that, even if investment cost of LED luminaires with active dimming are higher than the other, the costs generated in a 10year lifespan are minor.

Savings are not the only possible aim in a lighting retrofit. Meeting European standards for lighting in workplaces and improving lighting quality are also important requirements. Photometric measurements showed that the light environment before the retrofit didn't meet the European standards. The retrofit increased the level of the photometric parameters far above the minimum requirements of the standards as shown in ***Table 22***.

Table 22 *– Standard minimum requirements*

	Limit value	Pre-retrofit	Post-retrofit
Em	min 500 lx	180÷350 lx	518÷580 lx
Uo	min 0,6	0,5	0,8
UGR	max 19	<10	16÷18
Ra	min 80	84	83

The increment of lighting quality has been assessed also through the monitoring of other parameters and users survey. User satisfaction has been increased too and all the users declare to prefer the new lighting system.

7 . Concluding remarks and future aspects

This thesis had two objectives: Firstly, to monitor a lighting retrofit project from the points of view of energy efficiency, lighting quality, costs and user satisfaction. Secondly, to quantify the energy savings achievable thanks to the installation of new lighting source technology equipped with inbuilt control systems.

The first objective has been deeply fulfilled. The first chapters of the thesis explain the aspects that have been monitored and their importance as goals of a lighting retrofitting project. The monitoring of the case study covered many aspects of lighting retrofitting and can be used as example and guide offering tools, frameworks and methods to conduct any lighting retrofit analysis. However this case study was not a normal lighting retrofitting project. In fact the aim of this retrofit was to create an environment to assess the savings potential of the lighting retrofit technology while usually lighting retrofitting projects aim to reach well defined energy or economical savings or improvements in lighting quality. Normally the result of monitoring the retrofit is the assessment if savings or improvements have been reached, in other words monitoring is a way to verify if the retrofit has been successful or not. On the other hand in this retrofit project the monitoring wasn't a way to assess if the goal has been reached but the way to reach it. Since the scope was the assessment of the savings, the retrofit could be successful only if the monitoring was carried out accurately and precisely. This is the point of view from which looking at the results of the monitoring analysis. For example that fact that there is not a return of the investment shouldn't been read as failure of the retrofit project. Achieving economical savings was not an aim of the retrofit, while one of the aims was carrying out a reliable cost analysis.

The second objective is also completed successfully. The performances of lighting system with active dimming controls have been studied from the points of view of energy and economical savings and compared both to pre-retrofit conditions and to post-retrofit conditions without control system. Due to time constraint the evaluation of the saving is based only partially on metered values. Even if the reliability of assumptions made has been verified by comparison with literature and other studies, it would be really interesting carrying on the consumption monitoring and comparing the metered results to the computed ones. On one hand this would add reliability to the savings potentials evaluation for lighting source technology equipped with inbuilt control systems, on the other it would help verifying the reliability of the computed method to evaluate energy consumption presented by the European standard En 15193 and implemented in lighting simulation software such as Dialux.

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Appendix 1: General Questionnaire

LIGHTING CONDITION SURVEY

The aim of this questionnaire is to asset the opinion of occupants on the present lighting conditions. A luminous environment presents a complexity which is difficult to fully describe with the light environment measurements. The investigation of users' experience is a useful tool for a better understanding of this complexity.

When answering questions including scales, for instance:

Very much *Not at all,*

If the word on the left is appropriate, please mark the line on the far left edge, if the word on the right is appropriate; please mark the edge on the far right. If you have an intermediate opinion, please mark a place somewhere on the line between the two extremes. If you have a neutral opinion, please mark the middle of the straight line. To mark, please use a vertical line.

Very much *Not at all,*

Take your time when asked about your opinion regarding what you experience. Do not hesitate to consult the staff if you have any questions or doubts. Your personal opinion is of great interest to us, and will remain unrevealed to others than the scientific personnel taking care of the statistics.

Thank you very much for your time and cooperation.

Marta Gavioli
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050 316 0986

Building:……………………………………… Room number:……………. Date:……………………………
Time of the day:…………………… What´s the weather like **at the moment**? O Overcast O Sunny (no clouds)

1. Sex
   O Female O Male

2. Age
   O Under 30
   O 30-39
   O 40-49
   O 50-59
   O 60 and over

3. Are you right handed or left handed?
   O Right handed
   O Left handed

4. Do you wear glasses or contact lenses when working?
   O No
   O Yes

If yes

   O Simple
   O Progressive
   O Bi-focal
   O Contact lenses
   O Special glasses/lenses for VDU work

5. Do you consider yourself very sensitive to glare (do you often need sunglasses)?
   Very much |——|——| *Not at all*

6. How long have you been working in this room?...

7. How many days per week do you work in this room?...

8. In general how much time do you spend in your office or immediate work area?
   O All the time (7-8 hours a day)
   O Most of the time (4-6 hours a day)
   O Very little (less than 4 hours a day)
   O Other (please specify) ....

9. Which of the following tasks are a normal part of your job? Number each one you usually do as a part of your job with 1 for the most common activity.
   O Using PC or other keyboard machines
   O Reading
   O Writing by hand
   O Filing
   O Making drawings
   O Laboratory work
   O Using the telephone
   O Interviewing or holding small meetings
   O Supervising the work of others
   O Other (please specify) ....
   ....

10. Number the three physical features that are most important to you in making a work place a pleasant one for you to work in. Mark from 1 to 3, with 1 = the most important.
    O Comfortable temperature
    O Freedom from noise
    O Good light
    O Privacy
    O Good ventilation
    O Plenty of space
    O Window(s)
    O View out
    O General environment
    O Other (please specify) (colours, carpet, decoration, etc.).......................................

11. How satisfied are you with the following aspects of your work place?
    a. lighting
       Very satisfied |——|——| *Very dissatisfied*
    b. noise level
       Very satisfied |——|——| *Very dissatisfied*
    c. odour
       Very satisfied |——|——| *Very dissatisfied*
    d. ventilation
       Very satisfied |——|——| *Very dissatisfied*
    e. temperature
       Very satisfied |——|——| *Very dissatisfied*
    f. privacy
       Very satisfied |——|——| *Very dissatisfied*
    g. lots of space
       Very satisfied |——|——| *Very dissatisfied*
    h. view
       Very satisfied |——|——| *Very dissatisfied*
    i. general environment (colours, carpet, decoration)
       Very satisfied |——|——| *Very dissatisfied*

12. What is your general impression of your room/work area? (Mark as many as apply)
Pleasant Unpleasant
Interesting |——|——| *Monotonous*
Light |——|——| *Dark*
Evenly lit |——|——| *Unevenly lit*
Spacious |——|——| *Cramped*
Calm |——|——| *Noisy*
Informal |——|——| *Formal*

13. Do you like the appearance of your room luminaires?
Very much |——|——| *Not at all*
if not, what do you dislike?(too big, too thin, too squared, too ugly, etc.)
…………………………………………………………………….

14. Do you prefer working in natural light, artificial light or a combination of natural and artificial?
O Prefer natural
O Prefer artificial
O Prefer combination

15. In general how do you rate the light level, artificial and natural combined?
a. at the workplace
too much light |——|——| *too little light*
b. in the room in general
too much light |——|——| *too little light*
c. at the VDU
too much light |——|——| *too little light*

16. From your present location, do you experience any unpleasant gloomy (dark) areas in the room?
Very much |——|——| *Not at all*

17. From your present location, do you experience any unpleasant bright areas in the room?
Very much |——|——| *Not at all*

18. Do you have a desktop lamp or similar at your workplace?
O Yes
O No

If Yes, do you use it
O Always
O Often
O Seldom
O Never

If No: Do you think that a desktop lamp would improve your working conditions?
O Yes
O No

19. Do you often feel the need to manually adjust the light level in your room?
Often |————| *Never*

20. Can you control the natural light level at your workplace? (mark as many as apply)
O With external blinds or similar devices
O With internal blinds
O With curtains
O No

21. How often blinds are fully lowered?
Always |——|——| *Never*

22. Please read all the categories and then mark the kind of blind control is used in your room (only one alternative)
- o blinds fully opened all year round
- o automatic blinds: blinds are automatically fully lowered if there is too much light coming from the window. The blinds are fully opened otherwise.
- o manually controlled blinds: blinds are manually fully lowered if there is too much light coming from the window. The blinds are re-opened once a day, EVERY DAY, in the morning upon arrival.
- o blinds permanently closed (slat angle of 45°)
- o other (please specify) …………………………………
……………………………………………………………
……………………………………………………………
……………………………………………………………

23. When the electric lights are turned off, the work area is bright enough?
Always |——|——| *Never*

24. Do you ever work using only the light from the windows?
Always |——|——| *Never*
If it happens, can you specify when?
……………………………………………………………………

25. The luminaires in your room:
    O are all grouped together (they are all controlled by the same switch)
    O are dived into independent groups (every group is controlled by a different switch)

26. How often do you turn on only one group of luminaires, keeping the others off?
    Always |——|——| *Never*

27. Is the light level in your room adequate for you to complete all the tasks that are normal part of your job?
    O Yes, always
    O Yes, but sometimes I need to manually adjust the light level to be able to work (dimming, turning on the desktop lamp, shading the window, etc.)
    O no, sometimes I need to change workplace to complete the task

if no: when and which task?
……………………………………………………………………………………

28. Do you think the artificial lighting gives an appearance to the room which is:
    Too warm |——|——| *Too cold*

29. How would you assess the colour naturalness of the following objects under the artificial light?
    a. your hand
    Natural |——|——| *Not natural*
    b. your mobile phone
    Natural |——|——| *Not natural*

30. Does the artificial light ever cause glare strong enough to bother you?
    a. at the workplace
    Often |————| *Never*
    b. at the VDU
    Often |————| *Never*

31. Does the daylight ever cause glare strong enough to bother you?
    a. from the sky
    Often |————| *Never*
    b. from the sun
    Often |————| *Never*

32. Does the lighting cause reflections in your work material?
    a. from the ceiling lighting
    Not disturbing |——|——| *Very disturbing*
    b. from desk top lighting
    Not disturbing |——|——| *Very disturbing*
    c. from the daylight
    Not disturbing |——|——| *Very disturbing*

33. If there are reflections that disturb you, in what work material do they occur?
    O Glossy paper
    O VDU screen
    O Other (please specify) ....

    d. How important is it to you to have a window in your room or immediate work area?
    Important |——|——| *Not important*

34. How about the size of your window, is it:
    O too big
    O about right
    O too small

35. Are you able to see as much of the outside world as you would like from your workplace/desk?
    O Yes
    O No

36. Which of the following best describe the view out of the window closest to you? (Mark as many as apply)

O satisfying	O open
O limited	O bright
O simple	O uncluttered
O pleasant	O frustrating
O confined	O complex
O dim	O boring
O stimulating	O unpleasant
O cluttered	O spacious

37. Listed below are some of the advantages of windows. Mark the three that are most important to you at your workplace. Mark from 1 to 3, with 1 = the most important.
O Let you tell the time of day
O Let sunshine in
O Let you know what the weather is
O Let in warmth
O Let you see what is going on outside
O Provide light for plants
O A way for fresh air to enter
O View out
O Make room seem more spacious
O Break monotony
O Other (please specify) ....

38. Listed below are some of the disadvantages of windows. Mark the three that you feel are the biggest disadvantages at your workplace. Mark from 1 to 3, with 1 = the most important.
O Let in too much heat in summer
O Cause glare
O Let in too much cold air in winter
O Reduce privacy
O Limit ways furniture can be placed
O Let in outside noise
O Give too much sunlight
O Present a hazard (might brake)
O Present a hazard (person might fall)
O Other (please specify)..................................

39. If you have any further comments about the lighting please write them here:
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Thank you for completing the questionnaire.

Appendix 2: Users' survey

LIGHTING CONDITION SURVEY

ABOUT LIGHT AND DAYLIGHT IN THE ROOM

The main purpose of this questionnaire is to asset the opinion of room occupants on the present amount and quality of light.

When answering questions includes scales, for instance:

not at all ☐ ☐ ☐ ☐ ☐ ☐ ☐ very much

If the word on the left is appropriate, please mark the cell on the far left, if the word on the right is appropriate; please mark the cell on the far right. If you have an intermediate opinion, please mark an intermediate cell between the two extremes. If you have a neutral opinion, please mark the middle cell.

Please, before making evaluation take some time to become accustomed to the visual environment.

Do not hesitate to consult the staff if you have any questions or doubts.

Your personal opinion is of great interest to us, and will remain unrevealed to others than the scientific personnel taking care of the statistics.

Thank you very much for your time and cooperation.

Marta Gavioli
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050 316 0986

Room number:……………. Date:…………………………… Time of the day:…………………….

What´s the weather like at the moment? O Overcast O Sunny (no clouds)

1. How do you feel about the lighting in your room?

Very unpleased	☐	☐	☐	☐	☐	☐	☐	Very pleased
Very uncomfortable (visually)	☐	☐	☐	☐	☐	☐	☐	Very comfortable (visually)
Not stimulated	☐	☐	☐	☐	☐	☐	☐	Very stimulated

2. How do you consider the appearance of your room under this light condition?

Very colorless	☐	☐	☐	☐	☐	☐	☐	Very colorful
Very dim	☐	☐	☐	☐	☐	☐	☐	Very bright
Unevenly lit	☐	☐	☐	☐	☐	☐	☐	Evenly lit

3. In general, how do you rate the amount of light in the room?

Too low			sufficient			Too high
☐	☐	☐	☐	☐	☐	☐

4. Do you experience glare? Yes ☐ No ☐

5. How well can you see in this light?

Very bad ☐ ☐ ☐ ☐ ☐ ☐ ☐ Very well

6. Does the lighting system match your visual needs?

Not at all ☐ ☐ ☐ ☐ ☐ ☐ ☐ Yes, absolutely

7. How would you rate the colour of the light in your room?

Visually really cold ☐ ☐ ☐ ☐ ☐ ☐ ☐ Visually really warm

8. How would you rate the colour naturalness of the following objects under this light?
   I. *Your hand:*

   very unnatural ☐ ☐ ☐ ☐ ☐ ☐ ☐ very natural

   II. *Room furniture:*

   very unnatural ☐ ☐ ☐ ☐ ☐ ☐ ☐ very natural

9. Generally, would you prefer this lighting in your office room?

not at all ☐ ☐ ☐ ☐ ☐ ☐ ☐ very much

Thank you for completing the questionnaire