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Green Lighting

Energy-Efficient Integrated Lighting Systems

Auteurs:
Friedrich Linhart, EPFL – LESO-PB, friedrich.linhart@epfl.ch
Jean-Louis Scartezzini, EPFL – LESO-PB, jean-louis.scartezzini@epfl.ch

L'auteur de ce rapport porte seul la responsabilité de son contenu et de ses conclusions.

Summary

The objective of the Green Lighting project was to develop a High Performance Integrated Lighting System, based on advanced technologies for day- and electric lighting, achieving a Lighting Power Density (LPD) that does not exceed 3 W/m^2.

The project has revealed that Anidolic Daylighting Systems (ADS) are an ideal basis for High Performance Integrated Lighting Systems. Not only are they able to provide adequate illumination (i.e. sufficiently high illuminances) in office rooms during large fractions of normal office hours, under various sky conditions and over the entire year, but they are also highly appreciated by office occupants at the condition that glare control mechanisms are available. Complementary electric lighting is, however, still necessary to back up the ADS at times when there is insufficient daylight flux available. It was shown during this project, that the most interesting trade-offs between energy-efficiency and visual comfort are obtained by using a combination of ceiling-mounted directly emitting luminaires with very high optical efficiencies for ambient lighting and portable desk lamps for temporary task lighting. The most appropriate lamps for the ceiling-mounted luminaires are currently highly efficient fluorescent tubes, but white LED tubes can be considered a realistic option for the future. The most suitable light sources for desk lamps for temporary task lighting are Compact Fluorescent Lamps (CFLs) and white LED light bulbs. Based on the above-mentioned technologies, a High Performance Integrated Lighting System with a very low LPD has been developed over the last three years. The system has been set up in an office room of the LESO solar experimental building located on the EPFL campus; it has been tested intensively during a Post-Occupancy Evaluation (POE) study involving twenty human subjects. This study has revealed that the subjects' performance and subjective visual comfort was improved by the new system, compared to the usual lighting installation in this office. The High Performance Integrated Lighting System has an installed LPD of 4.3 W/m^2 and an effective LPD of approximately 2 W/m^2.

In conclusion, the Green Lighting project successfully demonstrated that installed LPDs lower than 5 W/m^2 and effective LPDs lower than 3 W/m^2 can be achieved today if advanced daylighting systems and efficient electric lighting components are integrated in an appropriate way. White LED applications can already be used nowadays in such systems; their potential in a short term will moreover continue to grow. OLED applications might also offer interesting options for the future, but this will still take several years.

Zusammenfassung

Ziel des Green Lighting Projekts war es, ein hocheffizientes, integriertes Beleuchtungssystem basierend auf modernster Tages- und Kunstlichttechnik zu entwickeln. Die Lichtleistungsdichte dieses Systems sollte den Wert von 3 W/m^2 nicht überschreiten.

Im Rahmen des Projekts konnte gezeigt werden, dass anidolische Tageslichtsysteme (engl. Anidolic Daylighting Systems (ADS)) eine ideale Grundlage für hocheffiziente, integrierte Beleuchtungssysteme sind. Solche Tageslichtsysteme sind nicht nur in der Lage, in Büroräumen über weite Teile der normalen Bürozeiten, bei verschiedenen Himmelstypen und über das gesamte Jahr eine adäquate Beleuchtungsumgebung (z.B. ausreichend hohe Beleuchtungsstärken) zu schaffen; vielmehr sind sie auch bei Büroinsassen sehr beliebt, vorausgesetzt dass geeignete Mechanismen zum Vermeiden von Blendungen vorhanden sind. Natürlich ist jedoch in jedem Fall zusätzlich elektrische Beleuchtung notwendig, um ein ADS zu Zeiten niedrigen Tageslichtflusses zu unterstützen. Im Rahmen dieses Projektes wurde gezeigt, dass die vorteilhaftesten Kompromisse zwischen Energieeffizienz und visuellem Komfort erzielt werden können, wenn für die elektrische Beleuchtung eine Kombination aus direktstrahlenden Deckenleuchten (Umgebungsbeleuchtung) und tragbaren Schreibtischlampen (temporäre Arbeitsbeleuchtung) verwendet wird. Als Leuchtmittel sind für die Deckenleuchten hocheffiziente Leuchtstoffröhren am besten geeignet, wobei weisse LED-Röhren eine interessante Option für die nähere Zukunft darstellen könnten. Für Schreibtischleuchten sind Kompaktleuchtstofflampen (sogenannte Energiesparlampen) oder weisse LED-Glühbirnen am besten geeignet.

Auf der Grundlage der aufgeführten Technologien wurde im Laufe der letzten drei Jahre ein hocheffizientes, integriertes Beleuchtungssystem mit extrem niedriger Lichtleistungsdichte entwickelt. Das System wurde in einem Versuchsbüro des „LESO Solar Experimental Building" auf dem Campus der ETH Lausanne aufgebaut; es ist im Rahmen einer wissenschaftlichen Studie mit zwanzig Versuchspersonen eingehend getestet worden. Diese Studie hat gezeigt, dass das neue Beleuchtungssystem in der Lage war, die Arbeitsleistung und den subjektiven Sehkomfort der Versuchspersonen im Vergleich zur Standardbeleuchtung in diesem Büro deutlich zu verbessern. Unser neues, hocheffizientes Beleuchtungssystem führt im Versuchsbüro zu einer *installierten* Lichtleistungsdichte von 4.2 W/m^2 und einer *effektiven* Lichtleistungsdichte von ungefähr 2 W/m^2.

Zusammenfassend lässt sich also sagen: Das Green Lighting Projekt hat gezeigt, dass installierte Lichtleistungsdichten unter 5 W/m^2 und effektive Lichtleistungsdichten unter 3 W/m^2 heutzutage realisierbar sind, vorausgesetzt es werden moderne Tageslichtsysteme und hocheffiziente elektrische Beleuchtungssysteme in idealer Weise miteinander kombiniert. Anwendungen auf der Basis weisser LEDs können bereits heute in solchen Systemen zum Einsatz kommen; in naher Zukunft wird das Potential dieser Technologie ausserdem immer weiter wachsen. OLED-Anwendungen (OLED = engl. Abkürzung für organische lichtemittierende Diode) könnten auch eine interessante Option für zukünftige Beleuchtungsszenarien in Büroräumen werden, bis dahin wird es aber wohl noch einige Jahre dauern.

Résumé

Le projet Green Lighting vise à concevoir et à mettre en œuvre un **dispositif intégré d'éclairage naturel et artificiel,** susceptible d'atteindre une puissance spécifique d'éclairage effective inférieure à 3 W/m^2.

Les composantes de base de ce dispositif sont des systèmes d'éclairage naturel à haute performance lumineuse, basés sur l'optique non-imageante (systèmes anidoliques). Ces derniers ont pour avantage d'offrir des niveaux d'éclairement très élevés sur le plan de travail, durant un grand nombre d'heures du jour et pour différentes conditions lumineuses extérieures, en cas de mise en œuvre dans des bâtiments administratifs ; leur appréciation par les usagers est, par ailleurs, extrêmement favorable pour autant que des moyens de gestion de la lumière naturelle réduisant les risques d'éblouissement soient mis à disposition. L'installation d'un dispositif complémentaire d'éclairage électrique demeure toutefois indispensable, en vue de pallier en particulier à l'absence d'éclairage naturel lors de périodes hivernales et/ou en début et fin de journée. Il a ainsi pu être démontré dans la cadre de ce projet qu'une intégration optimale de ces systèmes, tant du point de vue de la consommation énergétique que du confort visuel, peut être réalisée par l'installation de luminaires-plafonniers à haut rendement optique (mode d'éclairage direct) combinés à des dispositifs d'éclairage à la tâche (lampes de table) ; l'utilisation de diodes photo-luminescentes (LED), en lieu et place de tubes fluorescents à haute efficacité lumineuse, est certainement envisageable dans un futur proche, en ce qui concerne les plafonniers. Elle est déjà possible aujourd'hui pour les lampes de table (5 - 7 W), dans une mesure presque comparable aux lampes fluorescentes compactes (9 - 11 W).

Partant de cette approche, un **dispositif intégré d'éclairage naturel et artificiel,** caractérisé par une très faible puissance spécifique d'éclairage, a été conçu et mis sur pied dans l'un des locaux de bureau du bâtiment expérimental LESO, situé sur le campus de l'EPFL. L'étude de son comportement a été menée à bien par le biais d'un suivi expérimental et de l'évaluation subjective et objective de ses performances globales effectuée à l'aide d'une vingtaine de sujets. Il a ainsi pu être démontré que des performances et des conditions de confort visuel supérieures ou égales à celles d'un système conventionnel d'éclairage peuvent être offertes par un tel dispositif intégré. Il est apparu, par ailleurs, qu'une puissance spécifique d'éclairage installée égale à 4.3 W/m^2 pouvait être atteinte, ainsi qu'une puissance spécifique d'éclairage effective de 2 W/m^2.

Le projet Green Lighting a ainsi permis de montrer que des puissances spécifiques d'éclairage extrêmement faibles - inférieure à 5 W/m^2 pour la puissance installée et inférieure à 3 W/m^2 pour la puissance effective – peuvent être atteintes par le biais de l'intégration de systèmes d'éclairage naturel à haute performance lumineuse et de dispositifs d'éclairage électrique à haut rendement. Des diodes photo-luminescentes, émettant en lumière blanche (White LEDs), peuvent, par ailleurs, déjà être mises en œuvre dans de tels dispositifs: leur potentiel de développement à court terme est important. L'utilisation de diodes photo-luminescentes organiques (OLEDs) n'est par contre pas envisageable à court terme et requiert encore un certain nombre d'années.

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1   Introduction

1.1 Context of study

Artificial lighting is responsible for a significant fraction of the electricity consumption of buildings. As a consequence, up to 50% of electrical energy is used for that purpose in non-residential buildings (such as office and commercial buildings), contributing to the steady increase of the Swiss electricity consumption observed over the years [OFEN, 2008].

Electric lighting is often associated with light sources showing a low luminous efficacy (such as incandescent and halogen lamps), as well as inefficient lighting control strategies which neglect the possible contribution of daylight to indoor illumination and lead to excessive electric lighting needs [IESNA, 1984] [Scartezzini et al., 1993; Scartezzini et al., 1994]. This induces moreover a deterioration of thermal comfort during mid-season and summertime increasing the building cooling loads and related energy consumption for air conditioning [Stoot et al., 2003].

The important progress made in the lighting field both from a scientific and a technological perspective allows considering more sustainable lighting strategies today [Scartezzini and Courret, 2002; Philips Lighting, 2009] [Scartezzini, 2003]. An optimal integration of day– and electric lighting, based on a combined use of high efficacy light sources (HID lamps, fluorescent tubes, etc.) and optically efficient luminaries (based on non-imaging optics and highly reflective materials), can substantially reduce electric lighting needs within office rooms. It can furthermore improve the visual comfort conditions and sensory stimulation of the building users, contributing to the promotion and dissemination of these new lighting technologies in practice [Stone, 2000].

1.2 Project Goals

This project aimed to take advantage from the experience and knowledge acquired at EPFL in the domain of day- and electric lighting by the way of collaborations with partners of the lighting and construction industry [Scartezzini et al., 2000]. Within this framework the following specific objectives, regarding state-of-the-art and future lighting technologies, have been reached:

A.   High Performance Integrated Lighting Systems

Design, set-up and on-site assessment of the global performance of an integrated day- and electric lighting system – designated by Green Lighting technology - achieving a very low lighting power density (not exceeding 3 W/m^2).

B.   Future Lighting Technology

Analysis of the possibilities offered by novel light sources, such as Light Emitting Diodes (LED) and organic LED (OLED), expected to be suitable in the future for energy efficient indoor illumination [Philips Lighting, 2009; Hung et al., 2002].

The achievements of the project have been disseminated at the international level through participation to ECBCS Annex 45 *Energy Efficient Electric Lighting for Buildings* of the International Energy Agency (IEA); this was achieved in particular through a close collaboration with the participants of SubTask B *Innovative Technical Solutions* of IEA ECBCS Annex 45.

1.3 Project Planning

The two distinct objectives of the project have been achieved according to the following planning and detailed execution procedure:

A. High Performance Integrated Lighting Systems

- Setting-up of technical specifications for an integrated day- and electric system appropriate for non-residential buildings (e.g. office rooms);

- Analysis of different configurations of the integrated lighting system based on high-efficacy light sources (HID lamps, fluorescent tubes, etc.) and high-efficiency lighting luminaries (non-imaging optics, highly reflective materials, etc.);

- Optimization of the integrated day- and electric lighting system for non-residential buildings in order to achieve a Lighting Power Density (LPD) lower than 3 W/m^2;

- Selection and implementation of energy-efficient electronic gears (electronic ballasts) and daylight responsive electric lighting controllers (continuous light flux dimming);

- Design and full-scale implementation of the integrated day- and electric lighting system in a solar unit of the LESO solar experimental building (south oriented office room). This office room is shown in Figure 1.1.

B. Future Lighting Technology

- Analysis of future prospects offered by novel and future light sources (LEDs and Organic LEDs) regarding indoor illumination of non-residential buildings;

- Synthesis of results for the different light sources based on the technical specifications (luminous efficacy, lifetime duration, electronic control, etc.).

The two distinct objectives made up the Swiss contribution to IEA ECBCS Annex 45. The second one fitted mainly to the context of SubTask B *Innovative Technical Solutions* and more particularly to project B3 *Trends in existing and future lighting technologies.* Other outcomes, obtained at EPFL by the way of other research activities conducted in the field of lighting automation and control, contributed to SubTask C *Energy-efficient controls and integration* of ECBCS Annex 45.

Figure 1.1: Office room inside the LESO solar experimental building that served as test office room during the Green Lighting project.

2 Anidolic Daylighting Systems

2.1 Introduction

Over the last decades, various daylighting technologies have been developed, some of them having proven to be highly efficient [Scartezzini and Courret, 2002]. Performance assessments (obtained through simulation, monitoring and user satisfaction assessments) have recently become more and more available. Core-lighting applications (which typically collect daylight through lightpipes or skylights on a building's roof and then redistribute it into the building) [Al Marwee and Carter, 2006; Rosemann and Kaase, 2005] and side-lighting technologies (such as façade-integrated daylighting systems [Scartezzini and Courret, 2002; Ochua and Capeluto, 2006; Wittkopf, 2006; Wittkopf et al., 2006] have been subject to detailed analysis and have confirmed their energy saving potential.

One major problem often occurring in day-lit office rooms is over-provision of daylight flux near the window. The rear of the room, on the other hand, often appears gloomy. Consequently, occupants working next to the windows are often subject to glare. They therefore lower the solar blinds, electric lighting becoming necessary although the room could be completely day-lit if the daylight flux was properly distributed within the room.

Anidolic Daylighting Systems (ADS) [Scartezzini and Courret, 2002] are one type of very efficient façade-integrated daylighting systems; they are designed following the principles of non-imaging optics [Welford and Wilson, 1989]. Roughly speaking, non-imaging optics provide design methods for applications where high concentration factors of light matter more than sharp images. For the sake of the image being distorted, very high concentration factors become possible [Wilson et al., 2005]. The term "anidolic" has been chosen to describe non-image-forming daylighting devices that are strictly based on non-imaging optics: in Ancient Greek, "an" means "without" whereas "eidolon" signifies "image". ADS typically collect a maximal flux of daylight outside the building and redistribute it internally with a minimum number of reflections. They are specially designed to reduce the daylight flux that reaches the area next to the window and to raise the daylight flux to the rear of the room. Discomfort glare and gloomy areas can be avoided in this way.

2.2 Performance of a façade-integrated Anidolic Daylighting System

The south-facing side of the LESO solar experimental building (LESO building), located on the campus of the Swiss Federal Institute of Technology in Lausanne/Switzerland (EPFL), is equipped with a façade-integrated Anidolic Daylighting System (ADS) [Altherr and Gay, 2002]. The south elevation of the LESO building is shown in Figure 2.1. This southern façade is composed of 3 distinct ADS (one per floor of the building) which illuminate 14 office rooms, one seminar room and one mechanic's workshop.

Figure 2.1: South elevation of LESO building with façade-integrated Anidolic Daylighting System (ADS).

Figure 2.2 shows a schematic overview of one of these ADS as well as a detailed façade sketch. The system collects direct and diffuse daylight issued from the sun and the sky vault through a zenithal collector, composed of an anidolic element covered by a double glazing. Once the daylight flux has entered the system through the double glazing, it is redirected onto the room's diffuse ceiling by the anidolic element. From there, it is evenly distributed throughout the entire room.
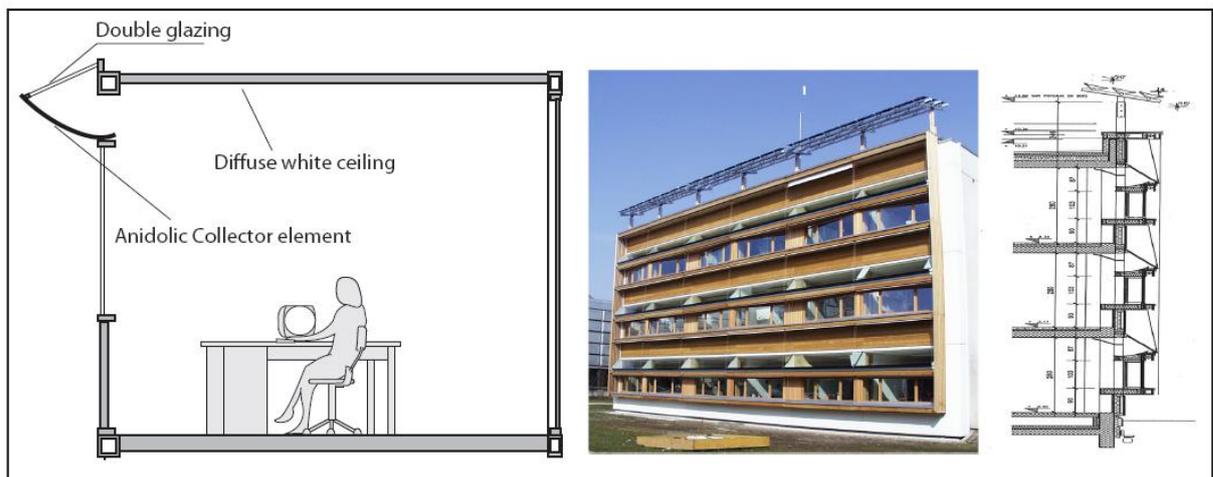
Figure 2.2: Schematic overview of one of the ADS-equipped office rooms (left) and detailed façade sketch (right).

This system has two great advantages compared to a normal vertical window:

1. The system blocks out large parts of the direct component of the daylight flux that would reach the room's window section through a vertical glazing. It therefore reduces the workplane illuminance as well as the luminances of objects and walls in this area. This contributes to reduced glare risks and improves visual comfort for occupants working next to the windows.

2. The blocked daylight flux is not rejected but redirected towards the room's diffuse white ceiling. From there, it is distributed comparably evenly within the room. The results are higher workplane illuminances in the centre and rear sections of the office room compared to the standard vertical window case.

The daylight performance of a given location in a specific office room can be characterized by the so-called daylight factor (DF):

$$DF(x) = \frac{E_i(x)}{E_{he}} \quad [\%]$$
(Equation 1)

In the above equation, E_{he} stands for the external horizontal illuminance (measured in Lux) and $E_i(x)$ stands for the internal horizontal illuminance at the distance x from the window.

Altherr and Gay have compared the daylight factors within the ADS-equipped office rooms at the LESO building to an identical office room equipped with a conventional double glazing. They reported daylight factors of 6.5% next to the windows, 5% in the centre of the room (2 m from window) and 2% at the rear (4 m from window) versus daylight factors of 11%, 3.5% and 1% in the corresponding parts of a room with a conventional double glazing [Altherr and Gay, 2002]. Figure 2.3 shows these results.
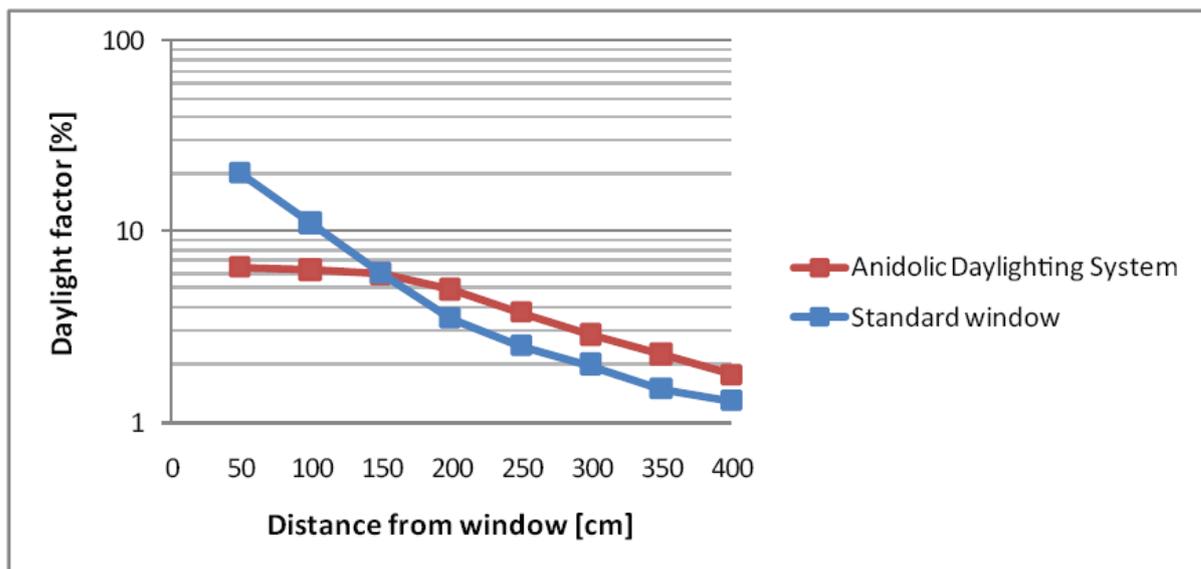
Figure 2.3: Daylight factors as a function of the distance from the window for the same office with and without ADS.

The overall performance of the LESO building is continuously monitored via a European Installation Bus System (EIB system). The system monitors and stores external data such as radiation and illuminance, temperature and wind speed as well as internal data such as horizontal workplane illuminance, blind movements and positions or occupancy levels. A detailed description of the system and the recorded data over the last few years is far beyond the scope of this report, such questions having been addressed in various other publications [Guillemin and Scartezzini, 2002; Lindelöf and Morel, 2006].

At this point, we will only take a look at the horizontal workplane illuminances measured in a test office room within the LESO building in order to get an idea on to what extent the lighting system in this office room is able to meet the lighting specifications for office lighting (such as workplane illuminances for instance).

Figure 2.4 shows the annual workplane illuminance data within the considered test office room for the entire year of 2006. For every month of the year, the illuminance measurements have been sorted in 1-hour bins (e.g. from 09:00 to 10:00) and the corresponding average illuminance has been calculated. Winter months (i.e. January to March) are plotted in blue, spring months (i.e. April to June) in green, summer months (i.e. July to September) in red and autumn months (i.e. October to December) in black. The required minimum illuminance (300 Lux) and the desirable illuminance (500 Lux) [Schweizerische Normen Vereinigung, 2003] are equally plotted in Figure 2.4. One can observe that during the entire year, the average workplane illuminances were largely sufficient from 09:30 to 16:00. Before 09:30, the average workplane illuminances were ranging for most months between 300 Lux and 500 Lux; for the months of December and January they were even lower than 300 Lux before 09:00. After 16:00, the average workplane illuminances dropped rapidly to values lower than 300 Lux in November, December and January. For all other months, the average workplane illuminances were higher than 500 Lux until at least 17:00.
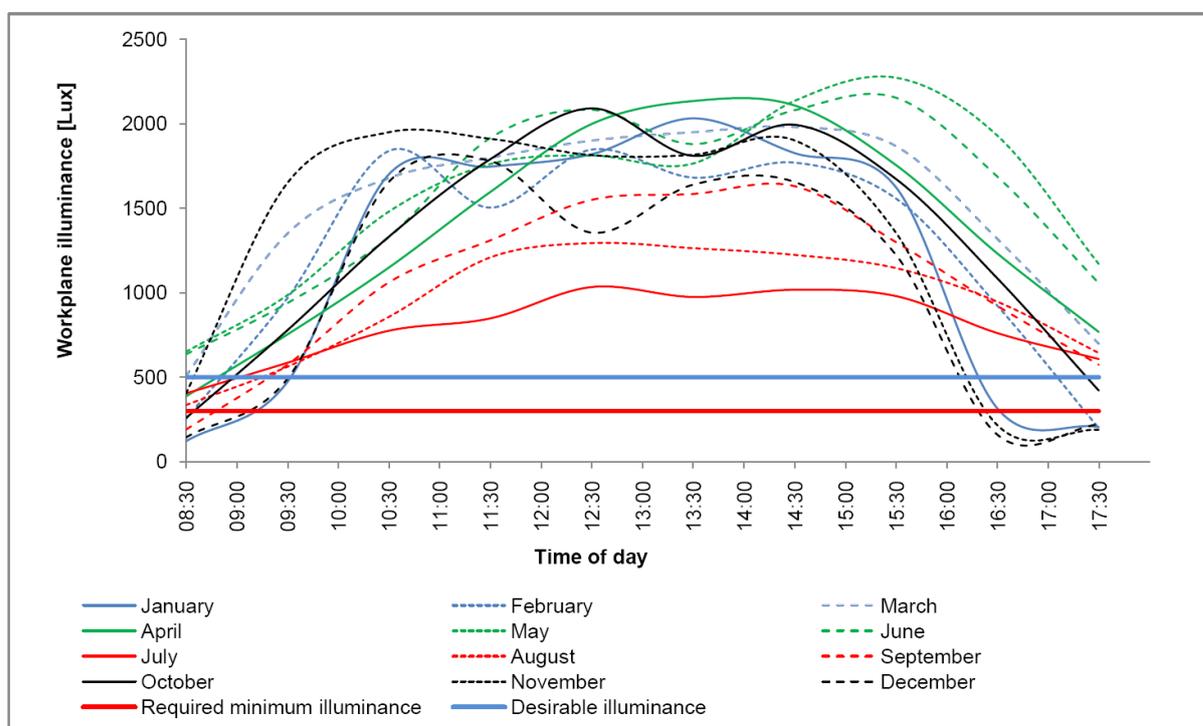

Figure 2.4: Annual workplane illuminance data within the considered test office room for the entire year of 2006.

The workplane illuminances plotted in Figure 2.4 are of course not exclusively due to daylight: the ceiling-mounted luminance-meter, on which the measurements of the illuminance data are based [Lindelöf and Morel, 2006], senses both day- and artificial light. Figure 2.4 doesn't make it possible to determine at which times additional artificial lighting was switched on in the room.

The following figures provide information on the number of times in 2006 when office occupants turned on electric lighting. Light switching actions are permanently monitored by the building integrated EIB system. Overall, artificial lighting in this test office room was manually switched on 119 times in 2006 by one of the office's occupants. Figure 2.5 shows the number of light switching-ons that occurred during each month of 2006. It is obvious that most switching-ons occurred in January, February, October and November. The comparably low value in December is due to maintenance work on the EIB system during that period. From March to September, less than 10 switching-ons per month were recorded.
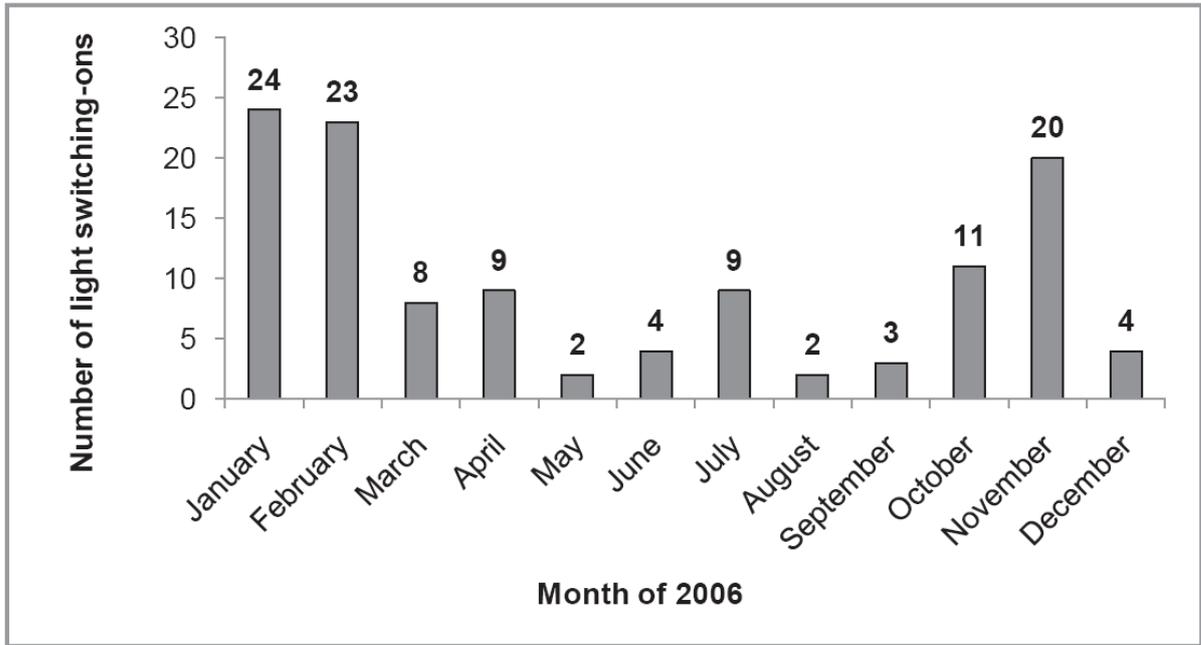
Figure 2.5: Number of light switching-ons that occurred during each month of 2006.

Figure 2.6 shows the number of light switching-ons for 2-hour time bins. More than 77% of all switching-ons occurred after 16:00. Even if the light switching data of this office room might not be completely representative for the entire LESO building, these results suggest that most switching actions occur after 16:00 and during the autumn and winter months. This, in turn, means that a large fraction of the illuminance data displayed in Figure 2.4 is due to daylight (especially close to noon and during the spring and summer months).
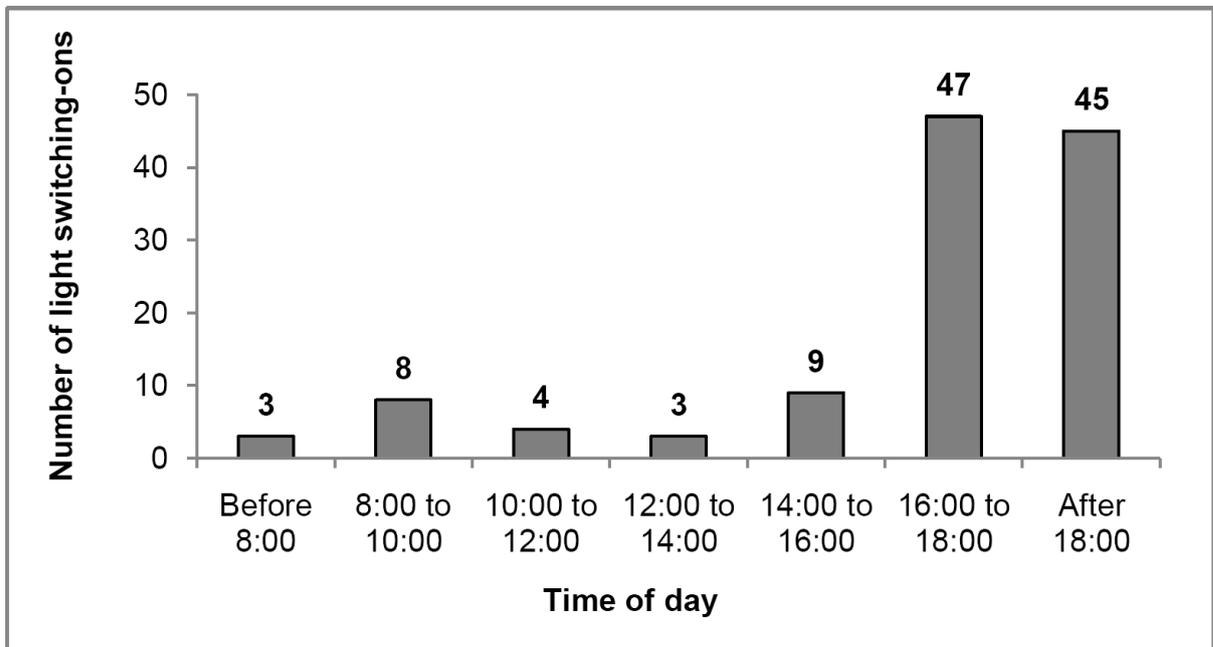
Figure 2.6: Number of light switching-ons for 2-hour time bins.

These observations indicate that the ADS displayed in Figure 2.2 offers a high quality natural illumination during large parts of normal office hours over the entire year: this is particularly true as much as the workplane illuminance (i.e. "the amount of available light") is concerned.

Complementary artificial lighting is mostly needed during evening hours in the autumn and winter months.

However, the performance of a daylighting system cannot be assessed only on the basis of achieved workplane illuminances. The system must also make it possible to reduce the risk of glare (occurring through daylight overprovision for instance). In the case of the LESO building, glare control is carried out by means of partly light-transmissive fabric blinds, two of which (one lower and one upper blind) are associated with each ADS (see Figure 2.7). The occupants manually operate these blinds at times when glare situations and too high illuminances occur. A detailed discussion of this blind configuration is given in Section 2.3.
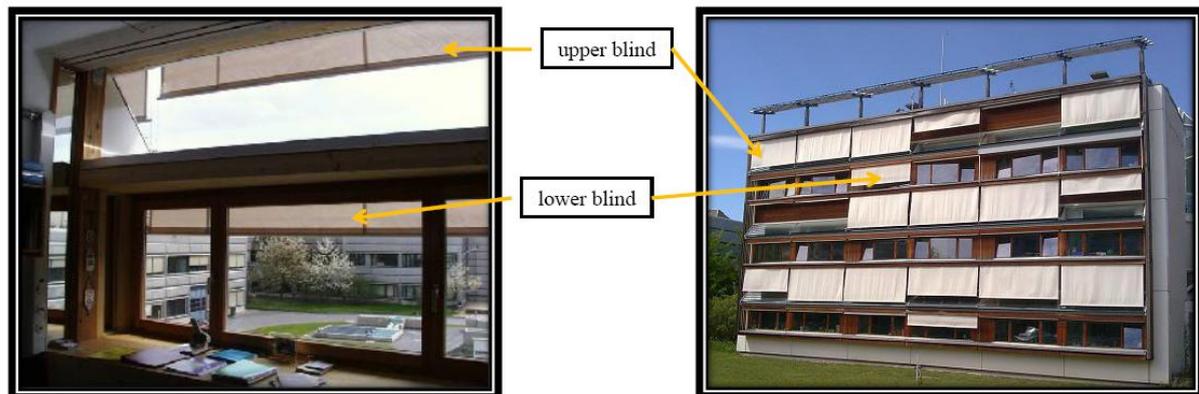

Figure 2.7: Inside view (left) and outside view of blind configuration at the LESO building.

Façade-integrated daylighting systems not only have to create a comfortable indoor lighting environment: an appealing external building appearance must also be offered. ADS are not only able to meet common aesthetic requirements of building design. They can even be used to emphasize a building's façade. The anidolic façade of the LESO building is well balanced from an architectural point of view. Its zigzag movement allows a clear distinction between the windows themselves and the anidolic elements [Altherr and Gay, 2002]. Another example of successful application of façade-integrated ADS is the refurbished building project of "Vakantiefonds Bouw" in Brussels/Belgium, suggested by Samyn and Partners in 1996 [Cardani, 1998].

The only existing ADS have been presented above. It is therefore not yet possible to quantify the cost of this installation in a reasonable way. Nevertheless, it can be assumed that a commercial façade-integrated ADS should not be 20 to 30% more expensive than a conventional façade, depending on material and construction costs. Costs for system maintenance are however low, the ADS being a passive device; a bi-annual cleaning of the system is by far sufficient [Linhart and Scartezzini, 2007].

2.3 Occupant satisfaction

During a study carried out in 2007 within the framework of this project, the occupant satisfaction within the LESO building was assessed by means of a Post Occupancy Evaluation (POE). The objective was not the development or the validation of a complex assessment method for occupant satisfaction in office buildings, but rather the identification of "weak spots" within the described ADS at the LESO building and the discussion of possible ways to deal with them.

It was decided to first assess occupant satisfaction with different aspects of their office lighting using a simple questionnaire. Twenty-nine persons working within the building at the time of the study (May and June 2007) had to be addressed; the questionnaire had to be easy to understand and quick to fill out in order to maximize the number of returned

documents. A simple and reliable questionnaire-based assessment method for occupant satisfaction regarding office lighting (Office Lighting Survey - OLS) was presented by Eklund and Boyce in 1996 [Eklund and Boyce, 1996]. Many questions within the OLS only allow an answer on a symmetrical, two-stage "Yes/No" scale. Akashi and Boyce, as well as Ramasoot and Fotios, have more recently used slightly modified versions of the OLS [Akashi and Boyce, 2006; Ramasoot and Fotios, 2007].

The original OLS has been adapted to the specific situation of the LESO building: a questionnaire with a mix of general, daylighting-specific and artificial lighting-specific statements was set up for that purpose. Occupants were asked to rate their agreement with each statement on a symmetric answering scale (i.e. without neutral choice) in order to avoid possible interpretation problems associated with neutral choices. In order to make the questionnaire more sensitive, a four-stage answering scale was used rather than the two-stage answering scale of the original OLS. This means that for each statement, occupants had the possibility to answer "1" (="yes"), "2" (="rather yes"), "3" (="rather no") or 4 (="no"). These four possible choices were assumed to correspond to 100%, 75%, 25% and 0% of agreement with the respective statement. Figure 2.8 shows the setup of the questionnaire; the entire questionnaire can be found in Annex 1.

(4)   Mon bureau me semble souvent trop lumineux.   OUI 1 2 3 4 NON

(5)   Mon bureau me semble souvent trop sombre.   OUI 1 2 3 4 NON

Figure 2.8: Setup of the questionnaire used during our Post Occupancy Evaluation (POE).

Table 2.1 shows 18 statements directly or indirectly linked to the ADS and its usage. The average agreement is given for each statement, as well as a decision of the status: "OK" means that the found agreement is located close enough to the optimal agreement (100% for some questions, 0% for others). It was arbitrarily decided that average agreement values that differ no more than 12.5% from optimal agreements are acceptable. In turn, values that do differ more than 12.5% from optimal agreements need checking because they might indicate the presence of lighting related problems.

Table 2.1 : Statements directly or indirectly linked to the daylighting system and its usage, together with the corresponding agreements and status, as used during our POE.

Nº	Statement	Agreement [%]	Status
1	J'aime la lumière dans mon bureau.	89.13	OK
2	L'éclairage de mon bureau est généralement plutôt confortable.	86.96	CHECK
3	Avec les équipements de mon bureau (fenêtres, stores, systèmes d'éclairage naturel, systèmes d'éclairage électrique) j'arrive à créer à tout moment une situation lumineuse qui me permet de bien percevoir mon travail.	89.13	OK
4	Mon bureau me semble souvent trop lumineux.	33.70	CHECK
5	Mon bureau me semble souvent trop sombre.	17.39	CHECK
6	J'ai souvent l'impression qu'il y a trop de lumière sur mon plan de travail.	21.74	CHECK
7	J'ai souvent l'impression qu'il n y a pas assez de lumière sur mon plan de travail.	14.13	CHECK
8	J'ai souvent des problèmes d'éblouissements (contrastes trop importants) dans mon bureau.	29.35	CHECK
9	Dans la plupart des cas, j'arrive à gérer rapidement les problèmes d'éblouissement (utilisation des stores facile).	84.78	CHECK
10	Je pense qu'il est important d'avoir de la lumière naturelle dans les bâtiments.	97.83	OK
11	C'est important pour moi en particulier d'avoir de la lumière naturelle dans le bureau où je travaille.	92.39	OK
12	Le contact visuel à partir d'une place de travail avec le monde extérieur me semble important.	97.83	OK
13	J'ai un contact visuel avec le monde extérieur à partir de ma place de travail particulière.	98.91	OK
14	Il y a assez de lumière naturelle dans le bureau où je travaille.	98.91	OK
15	Il y a trop de lumière naturelle dans le bureau où je travaille.	19.57	CHECK
16	La répartition de la lumière naturelle dans mon bureau est appropriée.	86.96	CHECK
17	A partir de ma place de travail, je remarque des modifications des conditions météorologiques à l'exté-rieur (soleil, nuages, pluie, etc.).	98.91	OK
18	La lumière dans mon bureau m'indique approximative-ment l'heure de la journée.	82.61	CHECK

At the end of the questionnaire, the study participants were asked to compare the office lighting situation within the LESO building to those in office rooms of other buildings where they had previously worked. Figure 2.9 shows the average agreement with the different possible statements "rather better", "about the same" and "rather worse". Almost 80% of all study participants feel that the lighting environment within the ADS-equipped office rooms in the LESO building is better compared than the one of their previous office rooms.
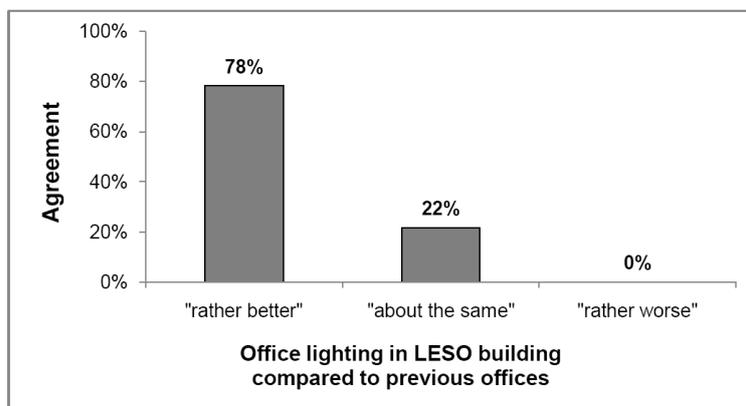

Figure 2.9: Average occupant agreement with the different possible statements "rather better", "about the same" and "rather worse" when asked to compare the lighting environment within the ADS-equipped office rooms within the LESO building to those of office rooms where they have previously worked.

The four-stage answering scale used within the questionnaires can be mathematically described by:

$$R_{x,n} \in \{0, 0.25, 0.75, 1\}$$ (Equation 2)

where $R_{x,n}$ stands for the respective answer to statement x by occupant n.

As mentioned before, an optimal answer $R_{x,opt}$ was also defined for each statement. In some cases, this optimal answer would correspond to 100% of agreement (e.g. when the occupant rated his agreement with the statement "In general, the lighting in my office is comfortable."). In other cases, the optimal answer $R_{x,opt}$ would correspond to 0% of agreement (e.g. when the occupant rated his agreement with the statement "My office often seems too bright."). We can therefore write

$$R_{x,opt} \in \{0, 1\}$$ (Equation 3)

where the appropriate value for $R_{x,opt}$ has to be chosen by the experimenter for each statement.

In the questionnaire, every single statement can be associated with one common problem often experienced in office lighting environments (e.g. glare occurence, "not enough light"-situations, missing windows, etc.). As previously mentioned, the objective of this study was to identify the "weak spots" of the ADS installed in the LESO building. In other words, we wanted to find out which of the commonly experienced office lighting problems were the most annoying to LESO building occupants. In order to quantify the specific annoyance of each of these specific problems within the building, a Mean Annoyance Value (MAV) [Linhart and Scartezzini, 2008] was defined for each statement. The MAV can be computed as follows:

$$MAV_x = \left| R_{x,opt} - N^{-1} \sum_{n=1}^{N} R_{x,n} \right|$$ (Equation 4)

where x stands for the respective statement and N stands for the overall number of persons who have returned the questionnaire. A MAV-value of 100% would correspond to a problem that is "totally annoying" to the occupants, whereas a MAV-value of 0% stands for "not annoying at all". The parameter MAV is used in the following for quantifying the extent to which a certain lighting related problem applies to the LESO building. The lower the MAV, the less annoying is the corresponding problem. Another parameter used in the following is the number of occupants directly concerned by a certain problem $N_{concerned}$. A person is considered to be directly concerned when he or she has replied opposite to the optimal answer $R_{x,opt}$ to a certain question (e.g. "yes" or "rather yes" when the optimal answer is "no").

A detailed evaluation of the average agreement values (see Table 2.1) determined by means of the 23 questionnaires returned by the LESO building occupants made it possible to get a good understanding of which typical lighting related problems may concern occupants in ADS-equipped offices the most. The twelve most persistent problems are listed in Table 2.2. The MAV and $N_{concerned}$-values are used to quantify the annoyance of the different typical problems.

Table 2.2: Most persistent lighting-related problems, associated MAVs and values of $N_{concerned}$.

N°	Problems	MAV [%]	$N_{concerned}$
1	Office seems too bright.	34	6
2	Glare problems.	29	6
3	Too much light on workplane.	22	3
4	Too much daylight in office.	20	3
5	Office seems too dim.	17	3
6	Glare problems difficult to handle.	15	3
7	Not enough light on workplane.	14	1
8	Daylight distribution not appropriate.	13	0
9	Difficult to find appropriate lighting configuration.	11	1
10	Outside view obstucted.	1	0
11	Not enough daylight in office.	1	0
12	Difficult to tell about outside weather conditions.	1	0

It can be observed that the maximum MAV is 34% and the maximum number of directly concerned occupants is 6. These low values underline the general impression that occupant satisfaction within the examined ADS-equipped office room is good. Furthermore, Table 2.2 shows that all problems scoring MAVs of 20% or higher are related to situations where too much daylight is bothering the occupants. Specific interviews with the six concerned occupants revealed that four of them manage to quickly "resolve" those "daylight overprovision"-problems using the blind systems in most cases. Two of them, however, found it not so easy to quickly resolve these problems. When looking at the $N_{concerned}$-value of problem N° 6, one might find it surprising that it equals 3 instead of 2. This means that there is one occupant who is not particularly annoyed by "daylight overprovision"-problems, but who still feels that those situations are not so easy to overcome in the rare cases where they occur. The MAV of problem N° 5 was found to be 17% with three directly concerned occupants. The latter were found to often work with fully lowered window blinds and do therefore often not benefit from the daylight flux offered by the ADS. The workplace of the person directly concerned by problem N° 7 is located at a considerable distance from the window.

The evaluation of the questionnaires made it possible to identify the main lighting related problems that concern the LESO building occupants the most. In order to find out which "weak spots" within the ADS are causing these problems, specific complementary interviews have been conducted with some occupants.

2.4 Global performance optimization

As explained in Section 2.3, the lighting-related problems that concern LESO building occupants the most are due to daylight overprovision. It is therefore necessary to take a close look at the sunshading devices installed within the ADS-equipped office rooms, to identify their "weak spots" and to find ways to optimize them.

Figure 2.10 shows the façade of the LESO building and the two types of fabric blinds that each office room is equipped with. The latter can be controlled via four manual switches inside the office (one "up" and one "down" switch for each blind). The upper blinds cover the ADS and are regularly used to reduce the room illuminance when the users feel that the daylight flux is too large in the office or that the office seems too bright; they are also used for glare control (i.e. to block out direct sunlight). The lower blinds are used less frequently by

most users and serve mainly for thermal protection. However, the interviews carried out during the study presented in the previous Section have revealed one important "weak spot" of this blind configuration. For technical reasons, small gaps remain between the blinds of the different offices (see Figures 2.10 and Figure 2.11 a)). At some moments of the day, these gaps can lead to glare problems in an office even though its respective blinds are lowered. These critical situations get even worse when the blinds of a neighbouring office are left open (e.g. due to occupant absence in this office). Figure 2.11 b) visualizes one potential way to deal with these problems: instead of installing all blinds at the same distance from the façade (as illustrated in Figure 2.11 a)), every second blind could be slightly shifted away from the façade, thus closing the gaps. On the other hand, such a modification might lead to shading of some offices by their neighbouring offices' blinds and therefore to conflicts between the building occupants.
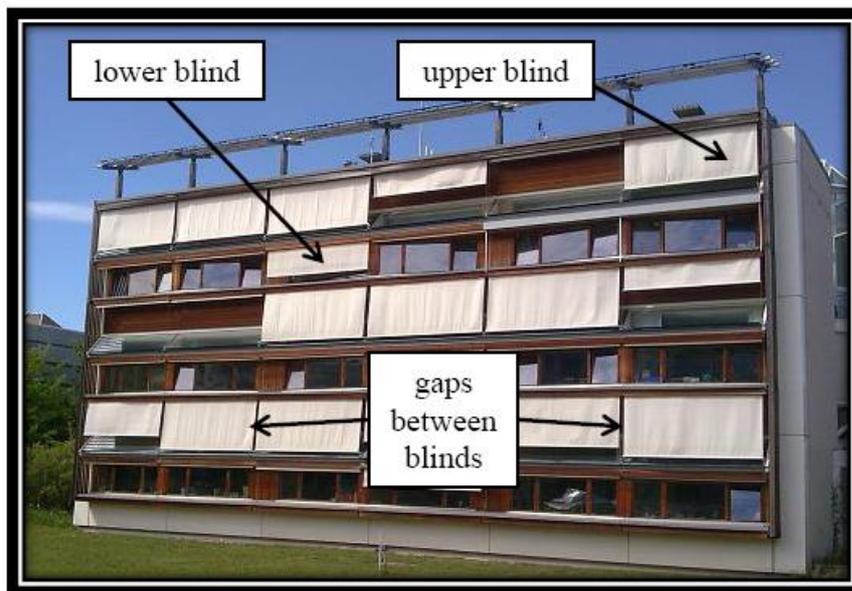

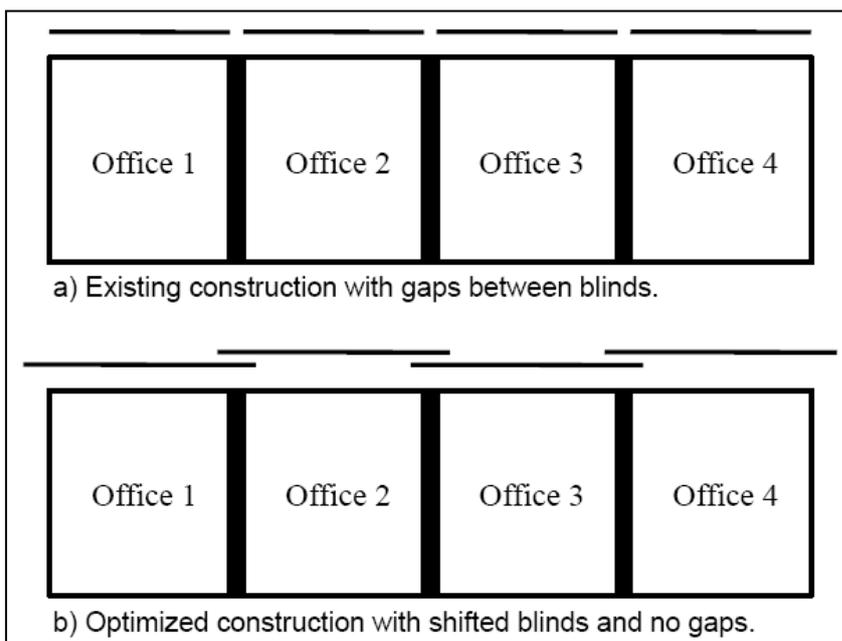**Figure 2.10: Gaps between the fabric blinds can lead to discomfort glare.**

Figure 2.11: Possible way to overcome the possible critical glare situations.

Another possibility to deal with the above mentioned critical situations would be to improve an internal, manual curtain system made out of fabric Californian blinds (see Figure 2.12) already installed within the offices. The occupants can manually open and close these curtains and also tilt the curtain elements around their vertical axes. However, these curtains do not seem to be frequently used and were described as "quite annoying" by some interviewed occupants. It might be indicated to think about installing a more adapted internal blind system. An additional "weak spot" pointed out by some occupants are the small lateral openings that exist between the different LESO building offices (see Figure 2.13). These lateral windows can sometimes cause glare to the occupants when the external blinds of their neighbouring office are open. The resulting annoyances could easily be avoided by installing an additional small blind at this point of each office.

Figure 2.12: Californian blinds installed inside the ADS-equipped LESO office rooms.

Figure 2.13: Lateral openings between the ADS-equipped office rooms.

Another point that the analysis of the questionnaires and the interviews revealed is the positioning of the manual blind switches inside the office rooms. As previously mentioned, four blind switches are installed in every room (see Figure 2.14). In some cases, the switches can easily be reached by the office occupants. In other cases, their workplaces are located at a certain distance from the switches: occupants have to leave their workplace to operate the blinds. The situation is worst in offices occupied by two persons: in such offices, one person is typically seated next to the switches, the other occupant having always to ask his colleague to operate the blinds for him. Even though this ensures a minimum of communication between the office workers, the regular demands for blind position adjustment can become a source of stress and distraction.

Figure 2.14: Manual switches for blind control.

Possible ways to resolve this problem would be the installation of additional blind control switches in office rooms with two occupants as well as the shifting of workplaces towards the switches in office rooms with only one occupant. However, this might not be easily feasible in many cases.

The specific building services at the LESO building offer a much more elegant way to deal with the blind control problem. As explained in Section 2.2, all lighting, heating and blind devices are actually interconnected via an EIB-system. Most switches and sensors installed within the building are also connected to the EIB-system. It is also possible to connect computers to the EIB-system. Figure 2.15 shows a schematic overview of the technical installation. Within the framework of the Green Lighting project, the possibility of using a portable server device ("MyHomeBox") for blind and luminaire control via the EIB-system was studied [Gavin and Dechamps, 2008]. It was demonstrated that it would be easily possible to give LESO building occupants the possibility to control their luminaires and blinds via a Flash™ application installed on their PC (see Figure 2.16) that communicates with the portable server device. Installing this application on all occupants' PCs is a very interesting option towards a global comfort enhancement within ADS-equipped offices.
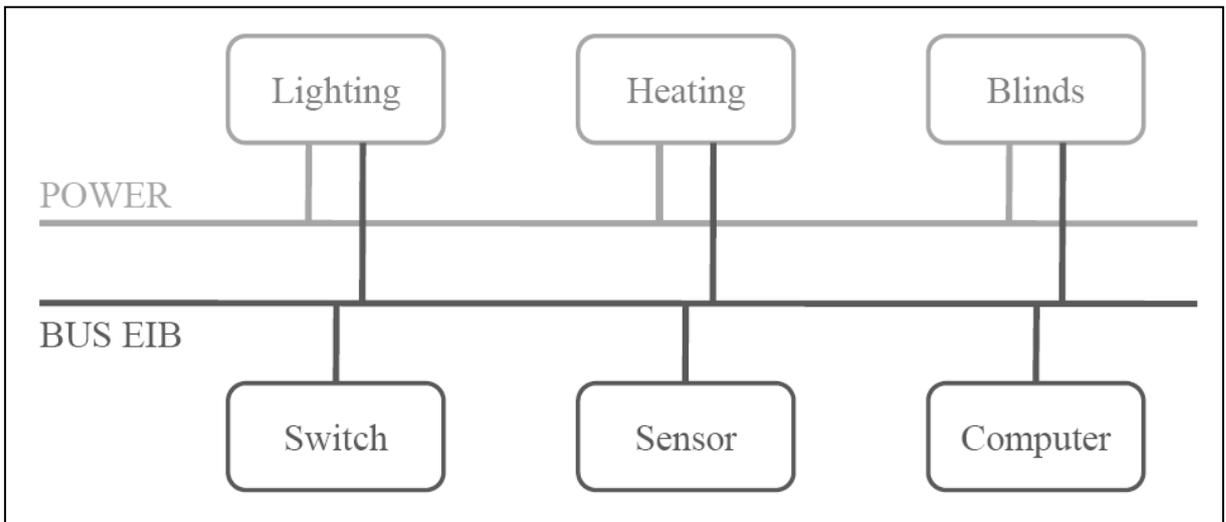

Figure 2.15: Schematic overview of the EIB-system installed within the LESO building.
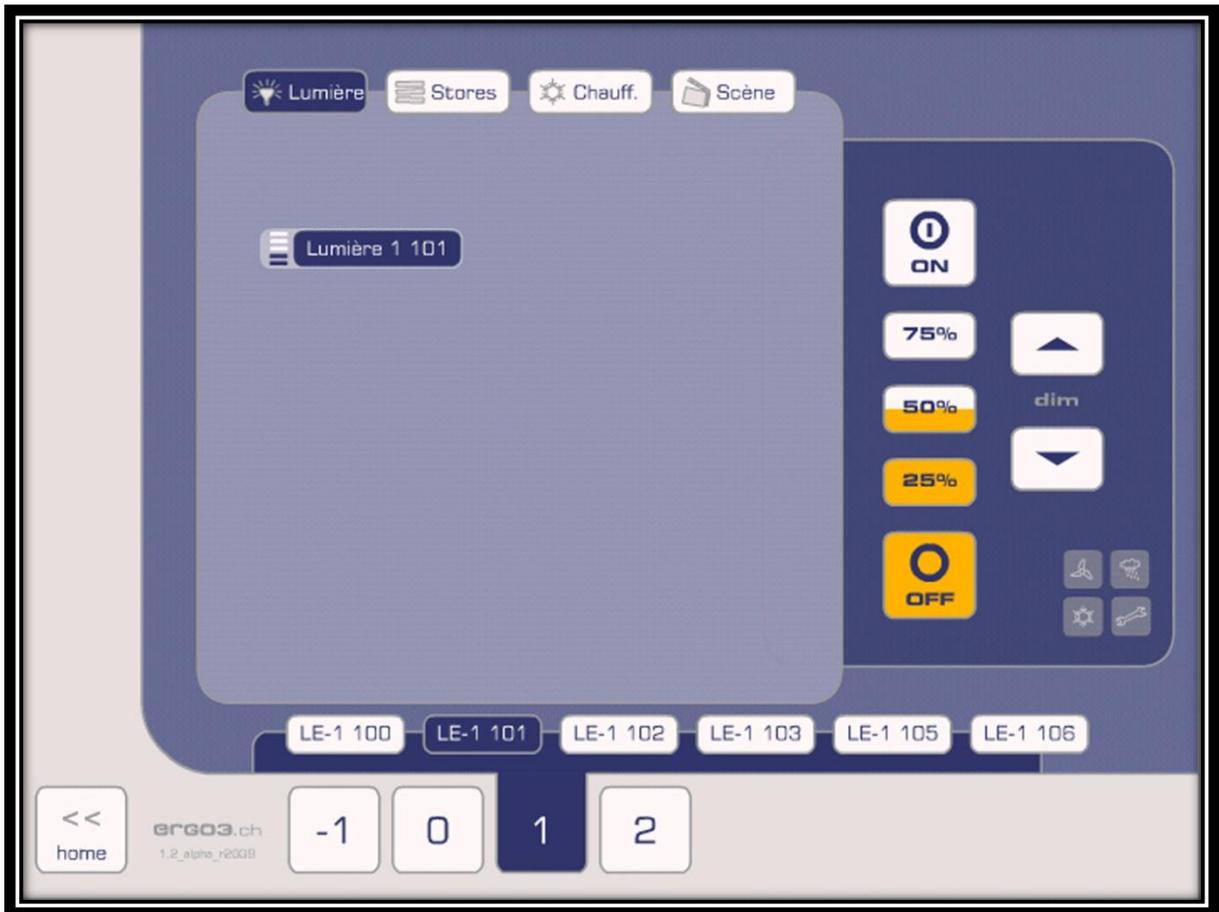
Figure 2.16: Screenshot of the Flash™ tool for blind control via PC, developed during the Green Lighting project.

Some of the reported critical situations within the examined ADS-equipped office rooms could be avoided by giving a short introduction on optimal ADS handling to some office occupants. Many problems revealed during this study (e.g. occupants feeling that their office is too dim or that they cannot find an appropriate lighting configuration) are indeed often the result of an inadequate ADS handling. Developing a comprehensive user manual for Anidolic Daylighting Systems could be an interesting option for further developments. One could also envisage setting up a 2-hour workshop, to be held from time to time in buildings with ADS-equipped office rooms, during which the positive effects of daylighting and the proper handling of ADS are explained.

Last but not least, one problem that has occurred from time to time at the LESO building is wind damage to the fabric blinds. Typically, strong gusts of wind rip some blinds off their fixtures (see Figure 2.17). Even though such damage has so far not caused elevated costs, it causes considerable annoyances. One possible way to avoid such damage could be to automatically open all blinds at times where high wind speeds occur. This could be done via the EIB-system, either based on wind speed recordings on the building's roof or based on current weather warnings (e.g. from Meteosuisse). The first solution is currently on the way of being implemented in the LESO building.

Figure 2.17: Wind damage to sun-shading devices at the LESO building

2.5 Conclusion

The results presented in this Section clearly show that the ADS installed within most office rooms of the LESO building are in general very well accepted by the building's occupants. There are, however, some issues that should be taken into consideration when installing ADS in other buildings. Our study has revealed that most of these critical situations are caused by temporary daylight overprovision inside the office rooms. Figure 2.18 gives an overview of the main issues and quantifies how annoying they are to the occupants.
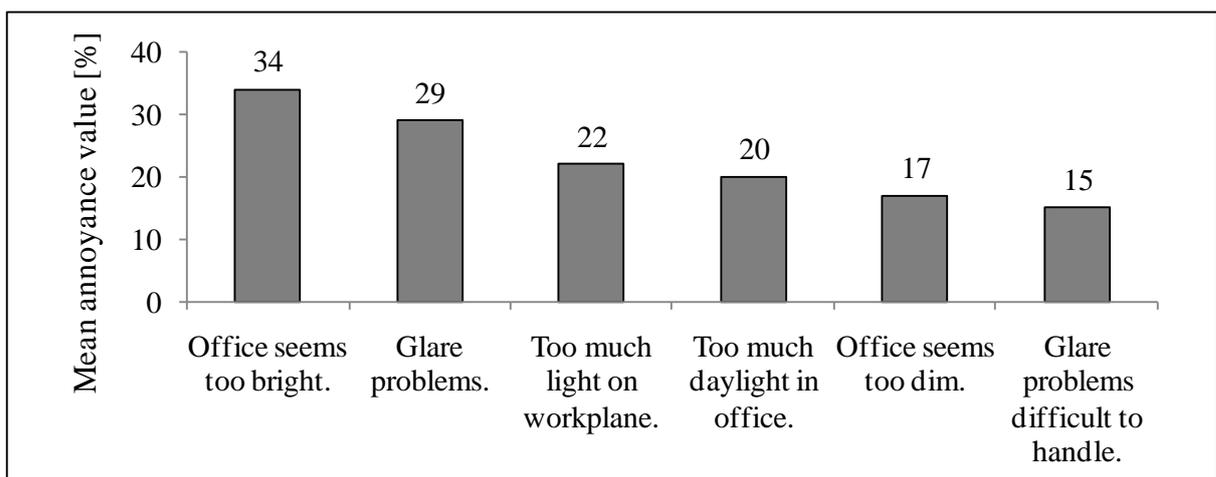
Figure 2.18: Overview of the main issues and their annoyance as determined during our POE.

It can be concluded that the annoyance of most critical situations revealed during our study could be drastically reduced by optimizing the blinds' configuration and control as well as by providing introductions on how to properly handle the ADS to the building's occupants. This can be of great interest to building designers and service engineers who may adopt similar systems for future buildings.

3   Electric Lighting Systems

3.1   Available lighting technologies

3.1.1 Light sources

The first versions of the incandescent lamp as we know it today (see Figure 3.1) was independently developed by Sir Joseph Swan in England and Thomas Edison in the USA during the second half of the 19th century. Edison patented his invention in 1879, and from then on, the invention spread rapidly into the entire world and became the commercial success that it has been for decades.

The "heart" of this light source is a filament that is heated by means of an electric current: the higher the temperature, the more light is produced. During the gradual improvement of Edison's invention over several years, it rapidly showed that tungsten was a material highly appropriate for this application: it has a comparably elevated melting point (3382°C) which permits elevated operating temperatures and consequently higher efficiencies. At its melting point, a tungsten wire has a luminous efficacy of 53 lm/W. However, in order to achieve acceptable lifetimes, incandescent lamps with tungsten filaments are operated at much lower temperatures with lower luminous efficacies. Typical values for incandescent lamps are situated between 10 and 20 lm/W, mainly depending on whether the bulb is gas filled or not. These luminous efficacies are low compared to alternative light sources. This is the reason why bans of incandescent lamps are currently discussed in many countries. Switzerland has banned incandescent lamps with very low efficacies (EU classes F and G) since 2009, but most commonly used incandescent light bulbs are still not affected by this ban. However, the corresponding EU regulations (that are also applied by many Swiss retailers) envisage a complete ban of most incandescent light bulbs by 2012. The incandescent light bulb as we know it therefore has to be seen as a phase-out model.

Figure 3.1: Incandescent light bulb.

Tungsten-halogen incandescent lamps (often simply called halogen lamps) achieve higher luminous efficacies and longer lifetimes than simple incandescent lamps. Such lamps have their bulbs filled with halogen gas, typically iodine or bromine. The halogen particles allow "burnt" tungsten molecules to recombine with the filament. Consequently, the latter can be operated at higher temperatures without decreasing the lifetime and better luminous efficacies (up to 30 lm/W) can be achieved. Halogen lamps are likely to be not affected by

the ban of incandescent lamps over the next few years and therefore remain an option for various lighting applications.

Figure 3.2: Halogen light bulb.

Fluorescent tubes can mostly be found in commercial, industrial and office buildings. They are typically composed of two electrodes that are connected via a long tubular light bulb. The interior of the bulb is coated with a mixture of different fluorescent powders (also called "phosphors") and contains a mixture of mercury vapor and inert gas. When a voltage is applied to the electrodes, an electric arc develops based on the current flowing through the mercury vapor. This discharge arc produces mainly UV radiation which excites the phosphor coating. The fluorescent responses of these phosphors then lead to light emission at various wavelengths within the visible spectrum. Fluorescent tubes cannot be operated without special current-limiting devices, so-called ballasts (see Section 3.1.3). They can be easily dimmed with electronic ballasts, are available in various lengths and diameters and have comparably long lifetimes. Fluorescent tubes reach luminous efficacies of around 100 lm/W.

Figure 3.3: Different types of fluorescent tubes (T8, T5 and mini).

Compact fluorescent lamps (CFL) are based on the same principles as fluorescent tubes, their main purpose being the replacement of conventional incandescent light bulbs. Figure 3.4 shows a typical CFL with an E27 socket and a bended glass tube. The electronic ballast is located between the socket and the tube. Due to the special geometry and the power

limitations of the electronic ballast, CFLs are somewhat less efficient than fluorescent tubes. Nevertheless, they still reach luminous efficacies higher than 60 lm/W and therefore represent a very interesting option for replacing conventional incandescent lamps.

Figure 3.4: Compact Fluorescent Lamps (CFLs).

Another lamp group that can be considered for office lighting is the so-called High Intensity Discharge (HID) lamp. All HID lamps produce light by means of two electrodes between which a discharge arc is established. Metals or halide compounds of metals are present in HID lamps, and when they evaporate into the arc, they emit light at characteristic wavelengths. Mercury lamps, sodium lamps and metal halide lamps are common types of HID lamps. The latter typically produce light by exciting several different atoms or molecules, for example sodium, scandium, thulium, holmium and dysprosium [IESNA Lighting Handbook, 2000]. Much like fluorescent lamps, HID lamps cannot be operated without special ballasts or electronic control gear. They reach luminous efficacies between 50 and 80 lm/W (for typical indoor lighting applications, i.e. 35 to 100 W), depending on the lamp type and the used control gear. Dimming HID lamps can be somewhat problematic because immediate dimming is not always possible. In addition to that, HID lamp applications often need considerable times to cool down before they can be started again (in order to maintain long lifetime). These characteristics are potential drawbacks for widespread use in office lighting scenarios.

Figure 3.5: High Intensity Discharge Lamp (HID lamp).

Over the last few years, light emitting diodes (LEDs) have witnessed a breathtaking development and have become widely available at competitive prices for various consumer products. Colored LEDs have been put to use as a source of emergency and decorative lighting, as indicator lamps, traffic lights and automotive applications for example. White LEDs have become more and more common for portable lighting solutions such as torches or bicycle lights but are not yet widely used as a light source for general lighting applications such as office lighting. However, white LED lamps for replacing incandescent light bulbs during retrofits reaching luminous efficacies of 20 to 25 lm/W (see Figure 3.6) are already available; this is also true for fluorescent tubes that can be mimicked by LED lamps (see Figure 3.7). White LED devices are believed by many to be "the light source of the future"; we therefore treat this technology separately in more in detail in Section 5 of this report.

Figure 3.6: LED lamps (for retrofit of incandescent light bulbs) [www.philips.com, 2009].

Figure 3.7: LED tubes (for retrofit of fluorescent tubes) [www.made-in-china.com, 2009].

In order to be able to accurately measure the luminous efficacy of various light sources, a test facility based on an Integrating Sphere (also called Ulbricht sphere) was set up at the LESO-PB during the Green Lighting project. The illuminance that a given light source creates at a point located in the sphere's inner wall is compared the illuminance at the same point created by a known reference flux; in this way, the light flux of any lamp can be accurately measured. The setup uses the so-called Absolute Integrating Sphere Method [Ohno, 1998]: instead of simply using a reference lamp inside the sphere that creates a known reference flux, a reference light flux is created using an external projector, a precision aperture and a luxmeter (which measures the illuminance that the projector's light flux creates at the precision aperture). In this way, our reference is not a lamp but the luxmeter itself. This is a great advantage because luxmeter calibrations are generally much more reliable than lamp calibrations. Figure 3.8 shows the measurement setup and gives an overview of luminous efficacies determined with this facility (red values). In addition to measured efficacies, values obtained by a high efficacy LED source and a T5 fluorescent tube are plotted in Figure 3.8 for comparison.
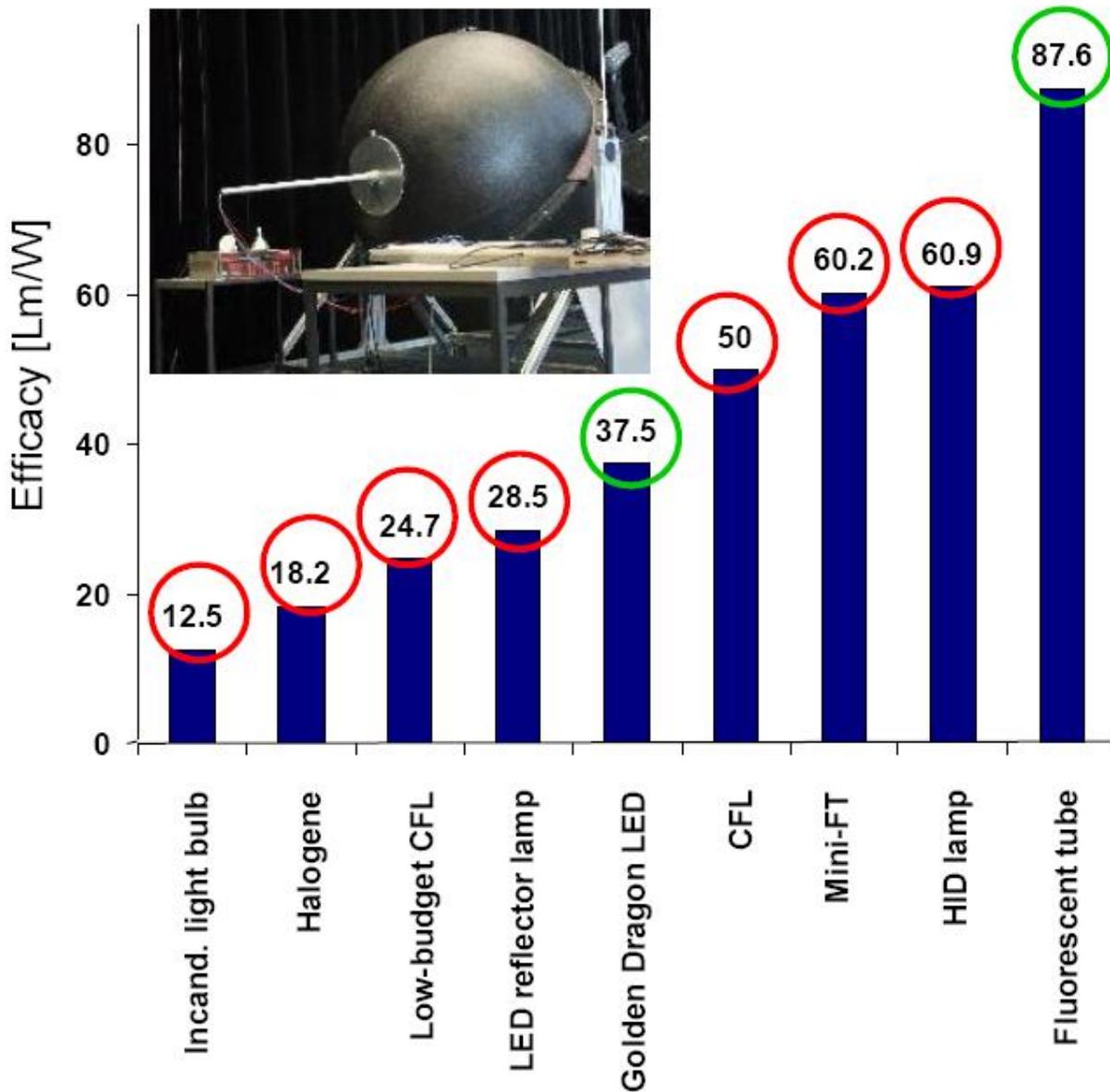
Figure 3.8: Setup of a lamp measurement facility at LESO-PB (Absolute Integrating Sphere method).

3.1.2 Luminaires

In order to create a comfortable indoor lighting environment, the light sources described in Section 3.1.1 are most of the time mounted in luminaires. Luminaires can be ceiling-mounted (attached directly to the ceiling or suspended at a certain distance from the ceiling) or free-standing.

The CIE Classification system for luminaires provides a classification system based on the upward and downward directed light flux output [IESNA Lighting Handbook, 2000]:

Direct lighting
Luminaires that direct 90 to 100% of the lamps light flux downwards. The light distribution may be widespread or concentrated, depending on the reflector material , finish and contour.

Semi-direct lighting
Predominantly downward light distribution (60 to 90%), with a small upward component to illuminate the ceilings and walls.

General diffuse lighting
Approximately equal downward and upward light distributions (40 to 60% in each direction).

Semi-indirect lighting
Luminaires that emit 60 to 90% of their output upwards towards ceiling and walls.

Indirect lighting
Mainly upward light emission (90 to 100%).

Figure 3.9 shows a ceiling-mounted luminaire for direct lighting (no light emitted upwards). The fluorescent light tube is mounted inside the luminaire and shielded by an acrylic glazing.

A luminaire for semi-indirect lighting is shown in Figure 3.10. This luminaire is not ceiling-mounted but free-standing. The advantages of such luminaires are their flexibility (office occupants can set them up where they like) and the fact that they create very comfortable lighting conditions (reducing glare risks). The drawback of such luminaires (and of semi-indirect lighting in general) is the fact that comparably large amounts of electric power are needed to create appropriate workplace illuminances.

In addition to the luminaires shown in Figures 3.9 and 3.10, which are mainly used for ambient and task lighting, there are also desk lamps which are mainly conceived for task lighting purposes. Such lamps typically offer direct lighting and can be used to complement ceiling-mounted or free-standing luminaires in office rooms. They can be switched on by the occupants at times where they need elevated illuminances for carrying out specific visual tasks on a very limited subsection of their workspace. Such a desk lamp is shown in Figure 3.11.

Figure 3.9: Two different ceiling-mounted directly emitting luminaires.

Figure 3.10: Mainly indirectly emitting luminaire.

Figure 3.11: Rather old-fashioned portable desk lamp.

The choice of appropriate luminaires is highly important when it comes to the design of energy-efficient lighting scenarios for office buildings. The luminaire efficiency (i.e. the ratio of luminaire output flux and lamp flux) must be as good as possible. In other words: luminaire losses, caused by multiple reflexions and light absorption, should be minimal.

3.1.3   Lighting control gear

As previously mentioned, some lamp types (such as fluorescent tubes, CFLs and HID lamps) cannot be operated without specific lighting control gear, so-called ballasts. Those ballasts are basically responsible for supplying the appropriate voltages and currents to the lamps electrodes at the right times. In HID lamps, the ballasts are also used for thermal management (if the lamp is too hot, the ballast stops the lamp from re-starting). For many years, magnetic ballasts have been used to operate fluorescent tubes. Such ballasts have various shortcomings, mainly in terms of energy-efficiency, dimability and flickering susceptibility; they are therefore more and more often replaced by electronic ballasts which overcome most of these problems.

In addition to simple electronic ballasts, entire electronic lighting control systems, which can be used to precisely address and control various types of lamp ballasts at the same time, become more and more current in office buildings. One of these lighting control systems is the Digital Addressable Lighting Interface (DALI). The use of the DALI technology within the framework of the Green Lighting project is explained in detail in Section 4.

3.2   Target and specifications

As explained in Section 2, ADS can have a large potential for becoming the basis of future energy-efficient office lighting designs. They would enable office workers to comfortably work under daylighting conditions during large parts of their working days, without even having to switch on any electric lighting. Nevertheless, even in such office rooms with abundant access to daylight and very effective glare control, the installation of complementary artificial lighting systems will always be necessary: office occupants have to be able to also work effectively during periods of darkness, for example in the early morning, late evening or when the outside sky is extremely dark (e.g. during thunderstorms).

The simplest design strategy for artificial lighting systems would therefore be a dimensioning for the worst case scenario (i.e. night-time with no daylight at all); however, this is probably not the optimal strategy for the design of low-energy office buildings which are mainly occupied during daytime. Dimensioning an electric lighting system for the nocturnal worst-case scenario can lead to unnecessarily high lighting loads during daytime because occupants might simply close the window blinds all the time (to avoid any kind of glare) and keep a powerful electric lighting installation switched on during the entire day. Taking this risk might make sense in some cases (e.g. in buildings where people regularly work at night), but definitely not in office buildings where people typically work during normal office hours (from 8:00 to 18:00, with some exceptions).

It is possible to characterize the artificial lighting load of an office room by calculating the lighting power density (LPD) for that room:

$$LPD = \frac{P_{con}}{A_{room}} \qquad [\frac{W}{m^2}] \qquad\qquad\qquad \text{(Equation 5)}$$

where P_{con} [W] is the overall connected lighting power in the office room and A_{room} [m^2] is the floor area.

One very simple but yet extremely effective way to reduce the electric lighting load of an office building is to minimize its office rooms' lighting power densities.

In the beginning of the Green Lighting project, the LPDs were determined for every south-facing office room of the building. It was found that the LPD was not identical for all ADS-equipped office rooms in the LESO building. Figure 3.12 shows the corresponding LPDs of the 15 south-facing LESO office rooms (all equipped with the ADS shown in Figure 2.2). Various combinations of different ambient and task lighting solutions lead to LPDs ranging from 4.5 W/m^2 to 13.7 W/m^2, the average value being equal to 9.1 W/m^2 [Linhart and Scartezzini, 2009]. Common values for average LPDs in Swiss office rooms normally range from 10 to 15 W/m^2. Li et al. for instance have recently described a comparable office room in the US with a value of 16.7 W/m^2 [Li, 2006].
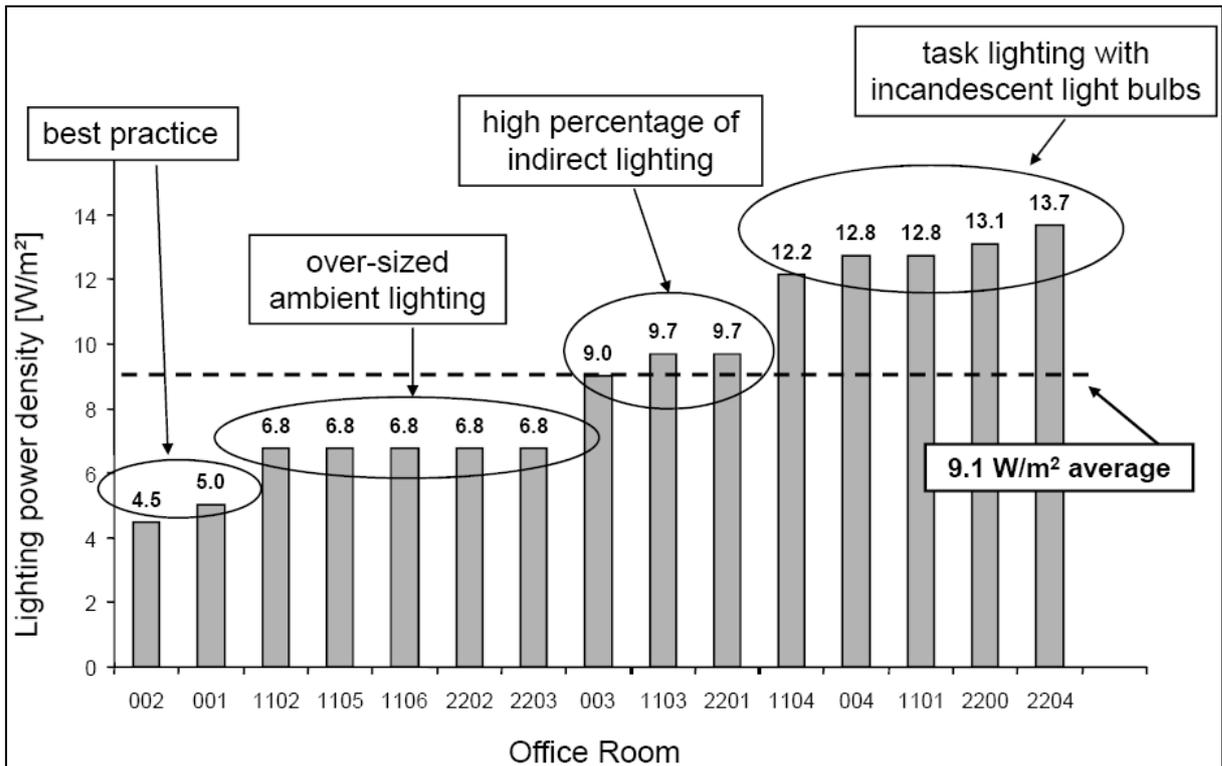
Figure 3.12: Lighting Power Densities (LPD) in the LESO building.

The differences in lighting power density (LPD) for the office rooms shown in Figure 3.12 have three main reasons:

1) Task lighting with incandescent lamps

Some occupants still use desk lamps with incandescent light bulbs (100 W, 80 W or 60 W) for individual task lighting. Compared to modern compact fluorescent lamps, those light bulbs are very inefficient; they cause a significant increase in LPD and can therefore lead to comparably large artificial lighting loads in the corresponding office rooms.

2) High fraction of indirect lighting

Some office rooms are equipped with mainly indirectly emitting luminaires. Such a luminaire is shown in Figure 3.10. (power consumption of 144 W). Most of the light flux is directed towards the room's ceiling and reflected from there. This creates a lighting environment that is in general highly appreciated by people, the drawback being that it also leads to comparably large LPDs and is therefore not optimal from an energy point of view.

3) Slightly over-sized ambient lighting

Compared to the "Best practice"-cases, some office rooms within the LESO building are equipped with three ceiling-mounted luminaires instead of two (office connected power of 108 W instead of 72 W). However, the following discussions will reveal that two ceiling-mounted luminaires seem to be sufficient in this particular building equipped with facade-integrated ADS.

The two "Best practice"-offices, with lighting power densities of 4.5 and 5 W/m^2, respectively, are both equipped with two ceiling-mounted luminaires with an optical efficiency of 69% (31% of the light emitted by the source is absorbed by the fixture). Each luminaire is equipped with one single 36W fluorescent tube. Both offices are occupied by two persons; one person uses a desk lamp equipped with an 8W compact fluorescent lamp (CFL) for individual task lighting.

Figure 3.13 visualizes in which way the average LPD within the LESO building would decrease if the three above weaknesses would be eliminated one after the other. Replacing

all incandescent light bulbs by comparable CFLs would already decrease the average LPD within the LESO building to an average of 8.3 W/m^2. Eliminating indirectly emitting luminaires by ceiling-mounted directly emitting luminaires would further decrease the average LPD to 7 W/m^2. Avoiding all over-sizing would lead to an average LPD of 5.5 W/m^2: for this last case, the assumption was made that all occupants are using an 8 W CFL desk lamp for temporary task lighting in addition to the ceiling-mounted luminaires.
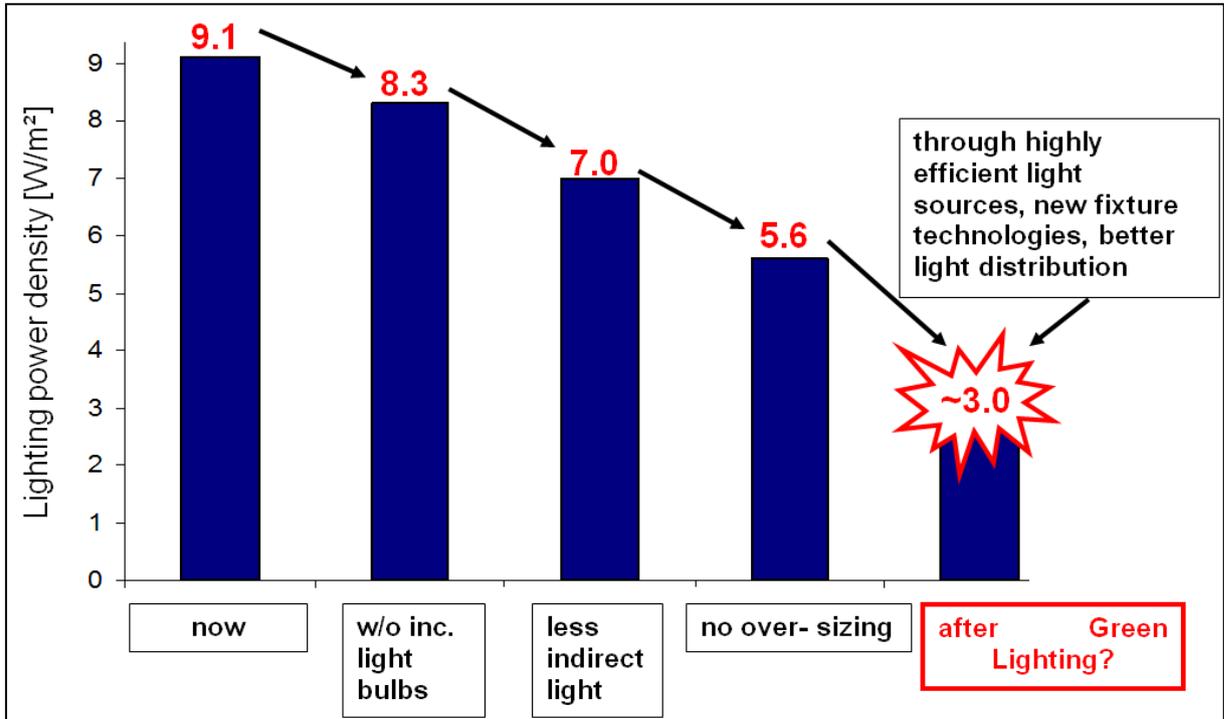

Figure 3.13: LPD reduction potential in the LESO building.

One of the objectives of the Green Lighting project was to evaluate possibilities to further reduce the LPDs in ADS-equipped office rooms as much as possible in order to keep the artificial lighting loads in such offices low and to save a maximum of electricity. A target LPD value of 3 W/m^2 was chosen: it was expected to reach this LPD target value through the use of highly efficient light sources, new fixture technologies and more appropriate light distributions.

Of course, the main purpose of an office lighting system is not to save electricity but to provide appropriate working conditions for the office occupants at all times. It has been shown in Section 2 that this is the case during large fractions of the working day in an ADS-equipped office room, especially when it is illuminated by daylight. When designing the complementary electric lighting system, the main concern is the necessity to offer an appropriate lighting environment when daylight is not available. Three extremely important questions concerning the visual comfort in an office room must be raised:

Is there enough light on the workplane to properly carry out visual tasks?

This question can be answered by looking at the illuminance that a specific artificial lighting installation is able to provide on the workplane, typically at 75 to 80 cm above floor level. The Swiss Norm SN EN 12464-1 [Schweizerische Normen Vereiningung, 2003] specifies minimum average illuminances between 200 Lux (archiving work) to 750 Lux (industrial drawing) for office rooms. As explained in Section 2, a required minimum illuminance of 300 Lux and a desirable illuminance of 500 Lux for our specific situation can be chosen as targets.

Is the light properly distributed on the workplane?

In order to offer an optimal visual comfort, it is not sufficient to simply achieve the necessary workplane illuminance: a certain illuminance uniformity must also be achieved. The Swiss Norm SN EN 12464-1 specifies that if the illuminance of a zone where a visual task is carried out is situated around 300 Lux, then the illuminances of the neighbouring zones should be situated around 200 Lux. Furthermore, the uniformities g_1 (i.e. the minimum illuminance on a reference plane divided by the average illuminance on that specific reference plane) must not be lower than 0.7 for zones where a visual task is carried out and not lower than 0.5 for the neighbouring zones.

Is the lighting installation causing significant discomfort glare?

Light sources can cause considerable discomfort if they have too large luminances or if they are inappropriately placed. Glare is not necessarily caused by the lamps themselves but can also occur due to light reflexions (e.g. on walls, furniture, screens or windows). By taking into account the workspace positions inside an office room when placing the lamps and luminaires in the room, glare risks can be reduced. This is particularly important for office rooms where the occupants mainly work with Video Display Units (e.g. with computers). One other way to reduce glare risks is the fostering of matt-finished rather than shiny surfaces. A possibility to quantify glare risks associated with a particular luminaire is to examine the so-called Unified Glare Rating (UGR). This value is often given by luminaire manufacturers for different viewing angles and room configurations. The Swiss Norm SN EN 12464-1 [Schweizerische Normen Vereinigung, 2003] specifies maximum UGR values from 16 (industrial drawing) to 25 (archiving work) for office rooms.

In Section 4, ways to minimize the LPDs in ADS-equipped office rooms while maintaining the necessary visual comfort conditions are discussed in detail.

3.3 Conclusion

It can be concluded that the most appropriate light sources for energy-efficient and yet comfortable office lighting scenarios are highly efficient fluorescent tubes and CFLs. However, white LEDs become more and more available and have a great potential for replacing parts of the fluorescent lighting installations over the next few years. As much as luminaires are concerned, directly emitting luminaires lead to the most energy-efficient lighting solutions, but indirectly emitting luminaires often offer better visual comfort. However, this enhanced visual comfort might not be necessary in all office rooms (e.g. in office rooms where artificial lighting is mainly complementary). For task lighting purposes, the use of portable desk lamps still makes sense. Electronic control gear has many advantages compared to conventional control gear, for example in terms of dimability, energy-efficiency and flickering susceptibility. In addition to that, electronic control gear makes it possible to use advanced lighting control systems (e.g. DALI technology).

In order to keep the lighting load in office rooms as low as possible, it makes sense to minimize the Lighting Power Densities (LPDs): power that is not installed cannot be switched on and can therefore not consume electricity. Of course, while minimizing LPDs in office rooms, one must not forget visual comfort: the illuminances inside the office rooms must be sufficiently high and must lead to appropriate uniformities. In addition to that, excessive discomfort glare must be avoided.

4 High Performance Integrated Lighting System

4.1 Definition

First of all, it makes sense to give a proper definition of the term "Integrated Lighting System". When hearing this expression, one usually first thinks of installations where one lighting system can deliver simultaneously daylight, artificial light or a combination of both. Such approaches have recently been described by Rosemann et al. and Mayoub and Carter [Rosemann et al., 2007; Mayoub and Carter, 2009].

However, the term "Integrated Lighting System" can also be used for lighting installations that are composed of separate day– and electric lighting systems but that have been planned using an *integrated approach* (i.e. an approach that takes into account natural light when planning the electric lighting system and vice-versa). Such an integrated, holistic approach can offer an optimal lighting environment with minimal electricity consumption for electric lighting.

When we use the term "Integrated Lighting System" here, we rather mean a lighting system that has been designed using an integrated, holistic approach than a lighting system where electric lighting components are integrated with daylighting systems.

4.2 System design and optimization

In Section 2.2, results of an occupant satisfaction assessment (POE) within the LESO building were presented. To assess the building occupants' satisfaction with the lighting environment of their offices, a questionnaire with general, daylighting-related and artificial lighting-related questions was distributed and evaluated. The results presented in Section 2.2 were considering the overall LESO building; they were split up into the two categories "'Best practice-offices" and "Other LESO offices". Figure 4.1 shows the occupants' agreements to the five following statements:

S 1:   "In general, the lighting in my office is comfortable."

S 2:   "The electric lighting system in my office is able to supply enough light."

S 3:   "The lamps in my office are in the right place."

S 4:   "I often have the impression that there is not enough light on my workplane."

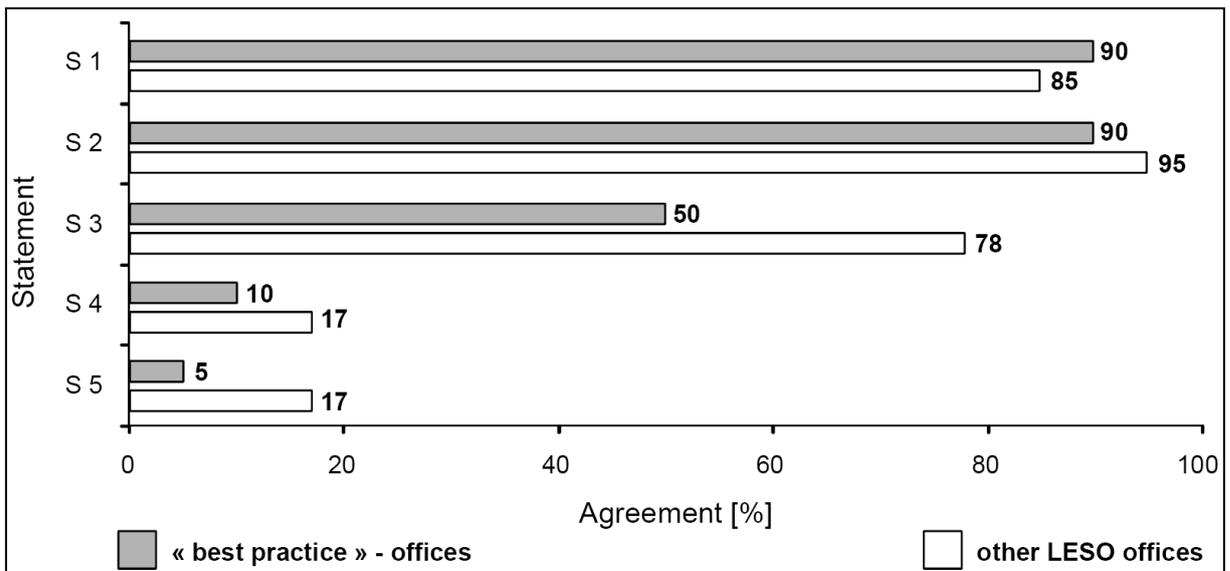S 5:   "My office often seems too dim."

Figure 4.1: Occupants' agreements to the five statements S1 to S5.

The average agreement with statement S1 was found to be 90% for the "Best practice"-offices and 85% the other LESO office rooms. Recent studies have found that agreement with statement S1 is typically around 70% in the US [Akashi and Boyce, 2006]. Supposing that the situation in Switzerland is comparable, all office rooms within this experimental building can be considered extremely comfortable as far as lighting is concerned. The high percentages of agreement with statement S2 indicate that the electric lighting is appropriate in all offices. The very low agreement levels to statements S4 and S5 indicate that "Not enough light"-situations are rare. Agreement values for statement S3 show that lamp positioning within the LESO building is not always ideal, especially in the case of the "Best practice"-offices. These results illustrate that all building occupants are highly satisfied with their office lighting environment and that this satisfaction does not depend on their offices' lighting power densities. In other words, occupants who work in the two "Best practice"-offices are as happy with their office lighting as their colleagues working in offices with more powerful electric lighting systems. In general, within the described ADS-equipped office rooms, occupant annoyance does rather arise from situations where there is *too much light* than from situations where there is *not enough light*.

Figure 4.2 shows the ceiling-mounted luminaire used in the two "Best practice"-office rooms. It is a Lip luminaire manufactured by Regent AG, with an announced efficiency of 69% (only direct light emission). The manufacturer describes this luminaire's reflector/diffuser unit as a "light directing element in clear synthetic material with prismatic cover in longitudinal axis and specular reflector Batwing in transvers axis" [Regent, 2009]. The incorporated HF electronic ballast is a Philips HF-R 136 TLD 220-240 with an announced power factor of 0.95. It is analogically dimmable by application of a DC Voltage between 0V and 10V. The switch/dimmer is located next to the door. Each luminaire is equipped with one 36W T8 fluorescent tube by Sylvania (RCI > 80, CT = 3000 K, light flux = 3350 lm). The resulting efficacy is 64 lm/W. Catalogue price in Switzerland is 381 CHF plus tax, which equals around 250 EUR.

Figure 4.2: Ceiling-mounted luminaire used in the two "Best practice"-office rooms. It is a Lip luminaire manufactured by Regent AG, with an announced efficiency of 69% (only direct light emission).

In order to properly assess the performance of the artificial lighting system composed of these two ceiling-mounted Lip luminaires, a computer model of the room has been set up using the ray-tracing software RELUX Vision [Relux, 2009]. Figure 4.3 shows the digital model of the LESO office room 001, one of the "best practice"-office rooms. The exact room geometry, furnishing, the ADS as well as most material properties (for example reflexion factors of walls, ceiling and floor and window transmission factors) have been measured and keyed into the model.
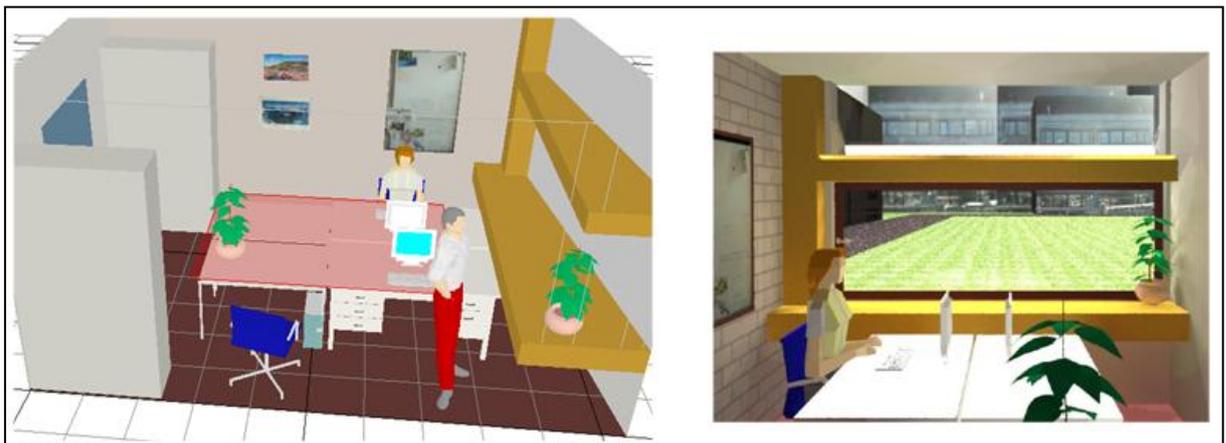

Figure 4.3: Digital model of the LESO office room 001, one of the "best practice"-office rooms.

Figure 4.4 shows the illuminance distribution within one "Best practice"-office for the current electric lighting installation (Lip luminaires and night-time conditions): only the electric lighting has been simulated with RELUX Vision. Five different reference planes (all 75 cm above floor level) have been considered during the simulations: entire office, larger workplane, workplane, as well as two individual workspaces. These individual workspaces have a size of 0.6 × 0.6 m and are located on those workplane areas where the two office occupants carry out specific visual tasks (e.g. writing or reading) that require reasonably high illuminances. This is a now usual choice for designing energy-efficient lighting situations [Hubalek et al.,

2006]. The simulated room contained no furniture in order to keep these initial simulations as transparent as possible.
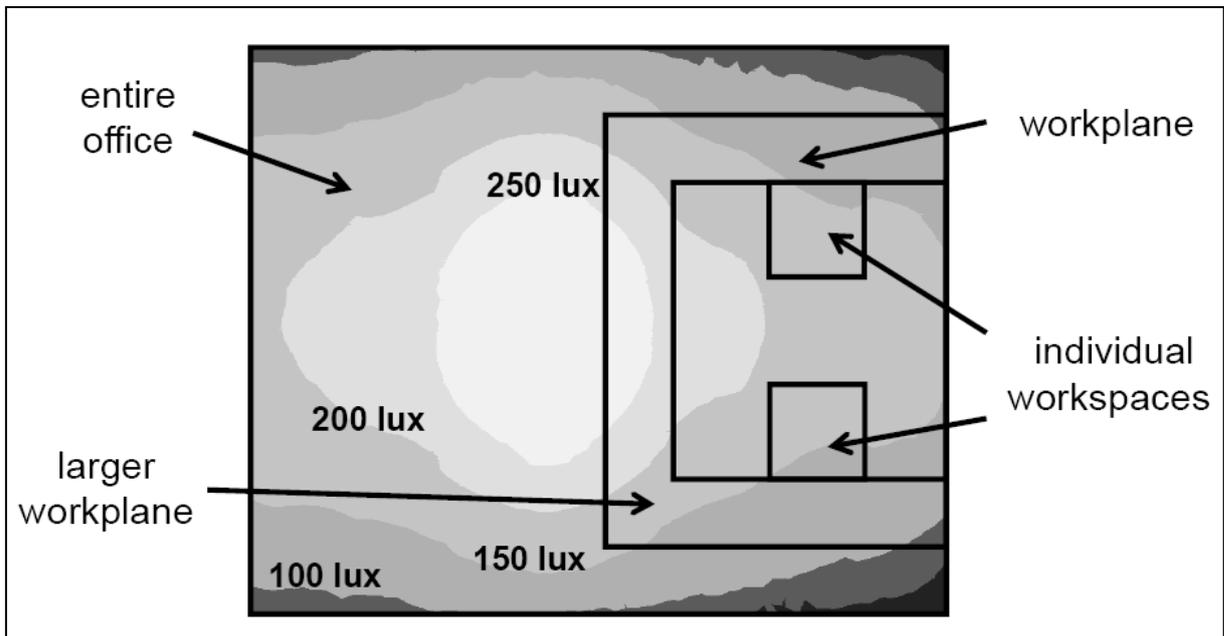

Figure 4.4: Illuminance distribution within one "Best practice"-office for the current electric lighting installation (Lip luminaires and night-time conditions).

The simulation results clearly show an illuminance maximum in the middle of the room, with illuminances ranging from 250 to 300 lux. This is coherent with the occupants' impression that *lamps within this office might not be in the "right place".*

Figure 4.5 summarizes the results of these first simulations in terms of average illuminances and uniformities.
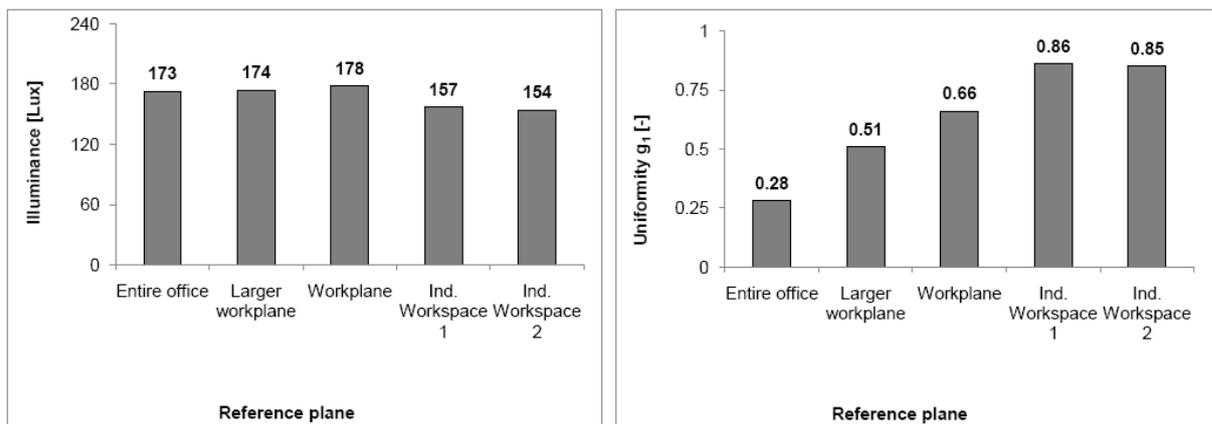

Figure 4.5: Results of the described first simulations in terms of average illuminances and uniformities.

It is important to note that illuminances are substantially lower than the values suggested by the corresponding standards (see Section 3). Nevertheless, the building's occupants feel that this lighting environment is extremely comfortable (see strong agreement with statement S1 in Figure 4.1) and that the electric lighting systems are powerful enough (see strong agreement with statement S2). One might argue that the academic usage of this building might not ensure that enough "old people" were represented in the study. As a matter of fact, older people tend to prefer higher illuminance levels. Our study, however, included six people

aged over 45 (three out of them even older than 55). All of them found that their office lighting was in general very comfortable and none of them judged low illuminances to be a problem. However, temporary task lighting seemed to be used somewhat more regularly by the older occupants than by the younger ones. One might further argue that any electric lighting system should be able to provide adequate illuminance levels at night (i.e. dimensioning for the worst case with no daylight at all). This is in principle true, but we believe that it is not the optimal strategy for the design of low-energy office buildings: dimensioning an electric lighting system for the nocturnal worst-case scenario can lead to unnecessarily high lighting loads during daytime because occupants might simply close the window blinds all the time (to avoid any kind of glare) and keep the electric lighting system switched on during the entire day. Taking this risk might make sense in some cases (e.g. in buildings where people regularly work at night), but definitely not in office buildings where people typically work during normal office hours (i.e. from 8:00 to 18:00, with some exceptions). In any case, the above results clearly show that an appropriate combination of Anidolic Daylighting Systems, thriftily dimensioned ambient lighting and temporary task lighting can lead to high acceptance levels amongst office workers.

Within the previous Section, we have shown that LESO building occupants are in general highly satisfied with their office lighting environment. In particular, we have shown that the lighting conditions within the "Best practice"-offices are comparable to those of the other LESO office rooms. It was decided to take the situation within these "Best practice"-offices as a starting point for developing new and even more energy-efficient electric lighting systems. If these new systems create lighting conditions similar to the one shown in Figure 4.4, one could assume that user satisfaction with the new lighting design will also be very high. Various designs of electric lighting systems were therefore simulated for the "Best practice"-offices using the RELUX Vision software. Figure 4.6 shows the illuminance distribution for two of them.
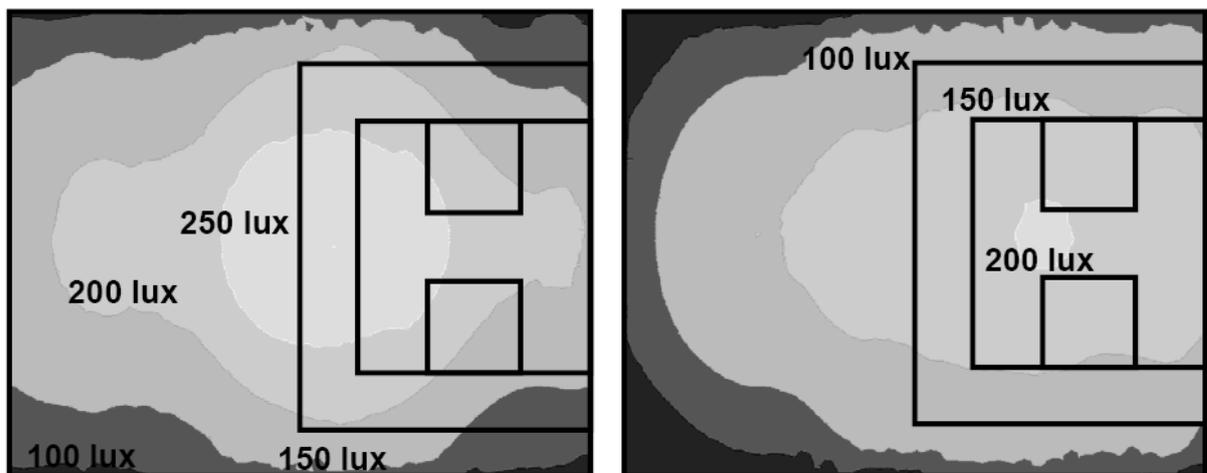

Figure 4.6: Illuminance distributions for the two new lighting designs.

In both cases, two ceiling-mounted luminaires with 96% optical efficiency have been chosen (Tulux ZEN3). Despite the fact that the manufacturer is not claiming that the latter is based on non-imaging optics, such a high efficiency can only be explained by the use of an "étendue" conserving optical design (while additionally assuring the use of highly reflective coating materials). This luminaire type is shown in Figure 4.7.
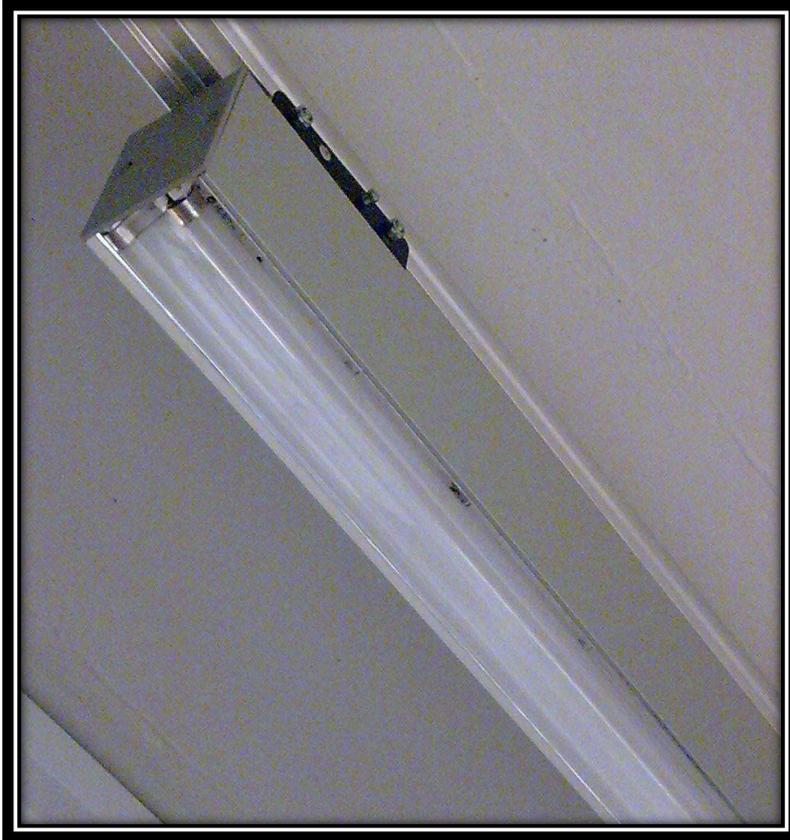
Figure 4.7: Tulux ZEN3 luminaire with an efficiency of 96%.

The ZEN3 luminaires, leading to the illuminance distribution in Figure 4.6 (left) are each equipped with one T5 fluorescent tube (28 W) and the corresponding electronic gear. The total power consumption of if this combination was measured and equals 31 W. The lighting power density for the simulated office room thus equals 3.9 W/m^2, including the electronic gear's power consumption. The simulation represented in Figure 4.6 (right) uses one T5 fluorescent tube (21 W) in each luminaire (system power consumption of 24 W). The resulting lighting power density (electronic gear included) is equal to 3W/m^2. Compared to the current situation represented in Figure 4.4, the new luminaires have been slightly displaced to the right. One can observe that the illuminance maximum has, therefore, also shifted to the right. This leads to higher illuminance levels on the workplane, compared to the rest of the room.

Figure 4.8 compares the current installation within the "Best practice"-offices with the two new lighting designs in terms of average reference plane illuminances.
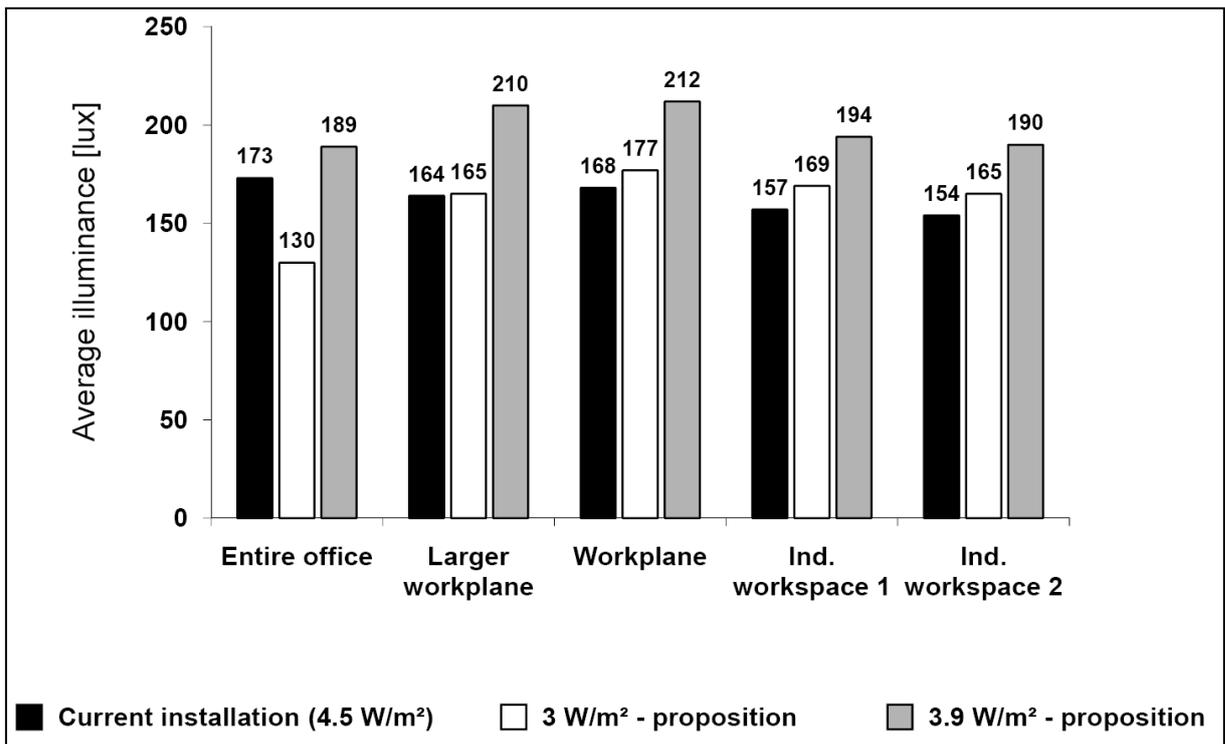
Figure 4.8: Comparison between the current installation within the "Best practice"-offices and the two new lighting designs in terms of average reference plane illuminances.

It can be observed that the 3.9 W/m^2-design leads to higher mean illuminances on every reference plane than the current installation. We can thus assume that this solution will not cause major difficulties as much as horizontal illuminances are concerned. The 3 W/m^2-design is also a potentially interesting option: except for the reference plane "entire office", the mean illuminances are slightly higher than those offered by the current installation. The lower illuminances towards the rear of the room might not cause major annoyances to the office occupants, since this is where the room's entrance is located.

However, as explained in Chapter 3, satisfaction with the lighting installation in an office room does not only depend on the supplied horizontal illuminances; another very important issue is the illuminance uniformity. Figure 4.9 shows a comparison between the current lighting installation and the two new designs in terms of uniformities g1 (i.e. the lowest illuminance on each reference plane divided by the corresponding average illuminance).
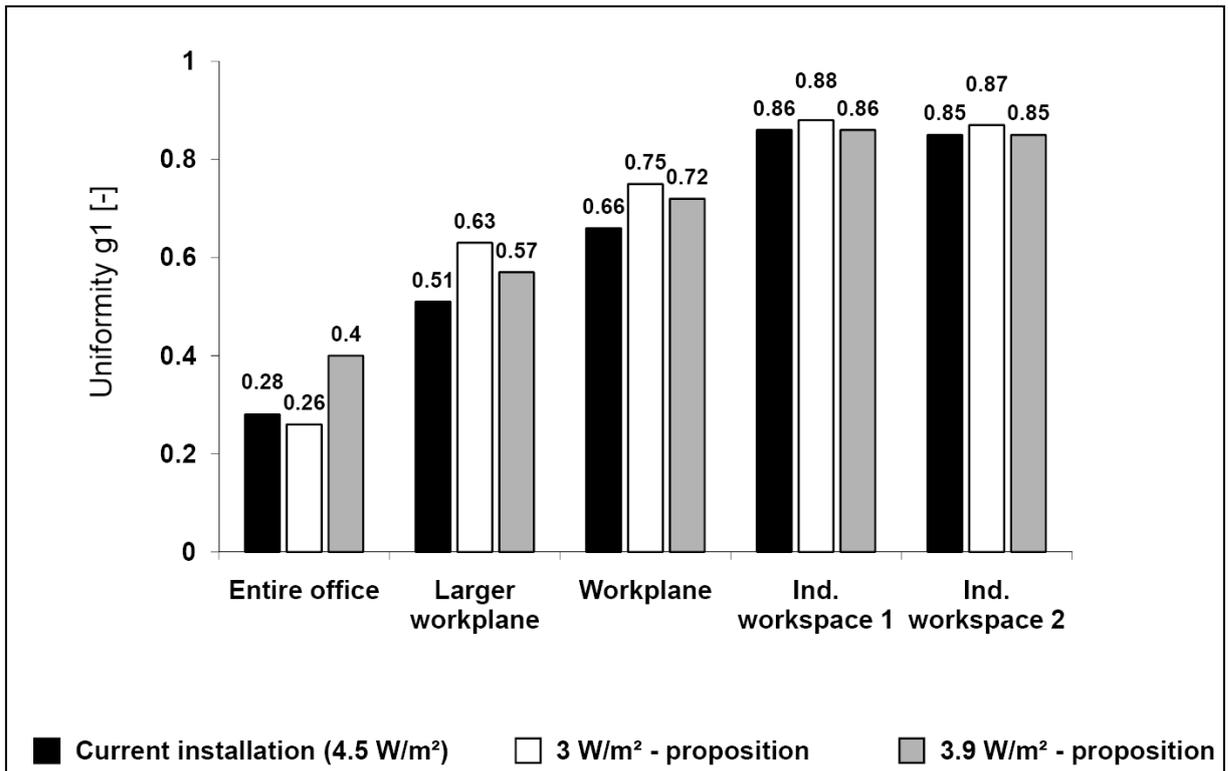
Figure 4.9: Comparison between the current installation within the "Best practice"-offices and the two new lighting designs in terms of uniformities.

It can be observed that the 3 W/m^2-design outperforms the current installation and the 3.9 W/m^2-design on every reference plane, except for the "entire office" plane. The uniformity values obtained with the 3.9 W/m^2-design are also equal or better than the values obtained for the current "Best practice"-solution.

In conclusion, the simulation results show that, at least as much as horizontal illuminances and uniformities are concerned, the two new lighting designs are fully comparable to the current solution (or even slightly better).

4.3 Experimental setup in the LESO building

In order to make the new lighting installation within a test room of the LESO building as flexible as possible, a rail system was mounted on the room's ceiling. This rail system is composed of aluminium rails on moveable carriages which allow the quick interchange and precise positioning of different luminaire types. Figure 4.10 shows the rail system with two mounted Tulux ZEN3.

Figure 4.10: Rail system with two mounted Tulux ZEN3.

The two ZEN 3 luminaires were equipped with one 28W warm-white T5 fluorescent tube (OSRAM FH 28W/830 HE) each and positioned as determined through the previous simulations carried out with Relux Vision in order to achieve the illuminance distribution of Figure 4.7.

Each luminaire is equipped with a DALI compatible electronic control gear (OSRAM Quicktronic Intelligent QTi DALI 1x28/54 DIM); this control gear is shown in Figure 4.11.

Figure 4.11: DALI compatible electronic control gear (OSRAM Quicktronic Intelligent QTi DALI 1x28/54 DIM).

Three different ways to control the ceiling-mounted luminaires have been tested during the Green Lighting project. The first two use the DALI-functions of the electronic control gear (ECG) shown in Figure 4.11. This requires an additional electronic component, a so called DALI controller. One of the most basic DALI controllers available, the OSRAM DALI Easy II, has been chosen for the Green Lighting project; it is shown in Figure 4.12.

Figure 4.12: OSRAM DALI Easy II, has been chosen for the Green Lighting project.

This controller is able to drive a maximum of 32 ECGs (as well as the associated luminaires and light sources). ECGs for halogen lamps and LEDs can also be controlled via the DALI Easy II.

Figure 4.13 shows the schematic wiring diagram of the test office room within the LESO building for the case where a DALI controller is used. Each of the two ECGs as well as the DALI controller is separately connected to the 240V power supply of the room. The DALI ports of the two ECGs are controlled via the output channels CH1 and CH3 of the DALI Easy II device, respectively. The input signal for the DALI Easy II control unit is issued either from a standard push button coupler, from a connected PC or from a remote control and associated infrared (IR) receiver.
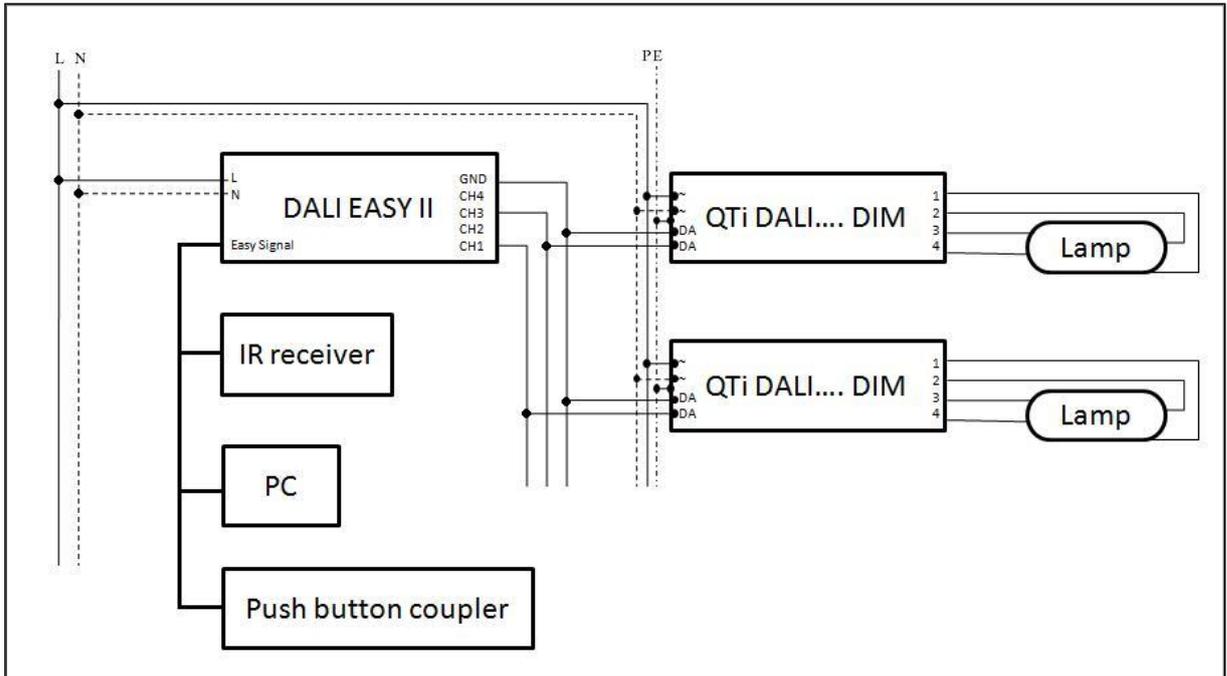
Figure 4.13: Wiring diagram of the test office room within the LESO building for the case where a DALI controller is used.

During the Green Lighting project, the control options "Remote control / IR receiver" and "PC" were tested.

Figure 4.14 shows the remote control as well as the IR receiver. The latter can be connected to the "Easy Signal" input of the DALI Easy II controller via a cable (2 m of length) and an RJ 11 connector.
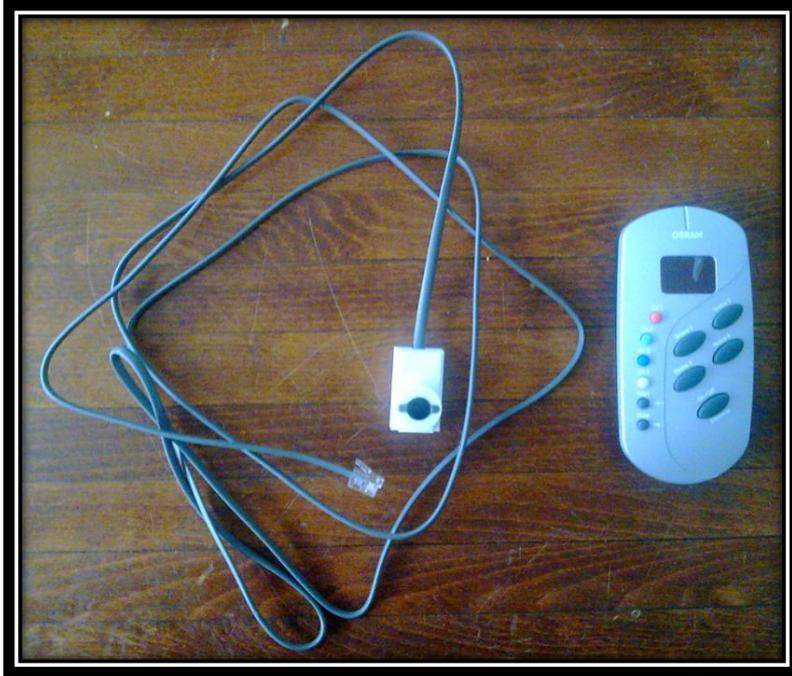
Figure 4.14: DALI remote control and IR receiver, as used during the Green Lighting project.

Each of the two ECGs and lamps shown in Figure 4.13 can be switched "on / off" and dimmed separately using the remote control. In addition to that, four lighting scenarios can be stored and easily selected afterwards.

The second possibility to drive the two Tulux Zen 3 luminaires tested during the project is to connect a PC to the "Easy Signal" input of the DALI Easy II control unit (see Figure 4.12); this is done via a USB / RJ 11 adapter. The OSRAM software tool "EASY Color Control" can then be used to communicate with the two ECGs (see Figure 4.11) and the attached luminaires via the DALI Easy II control unit. Figure 4.15 shows a picture of the USB / RJ 11 adapter and a screenshot of the software tool.
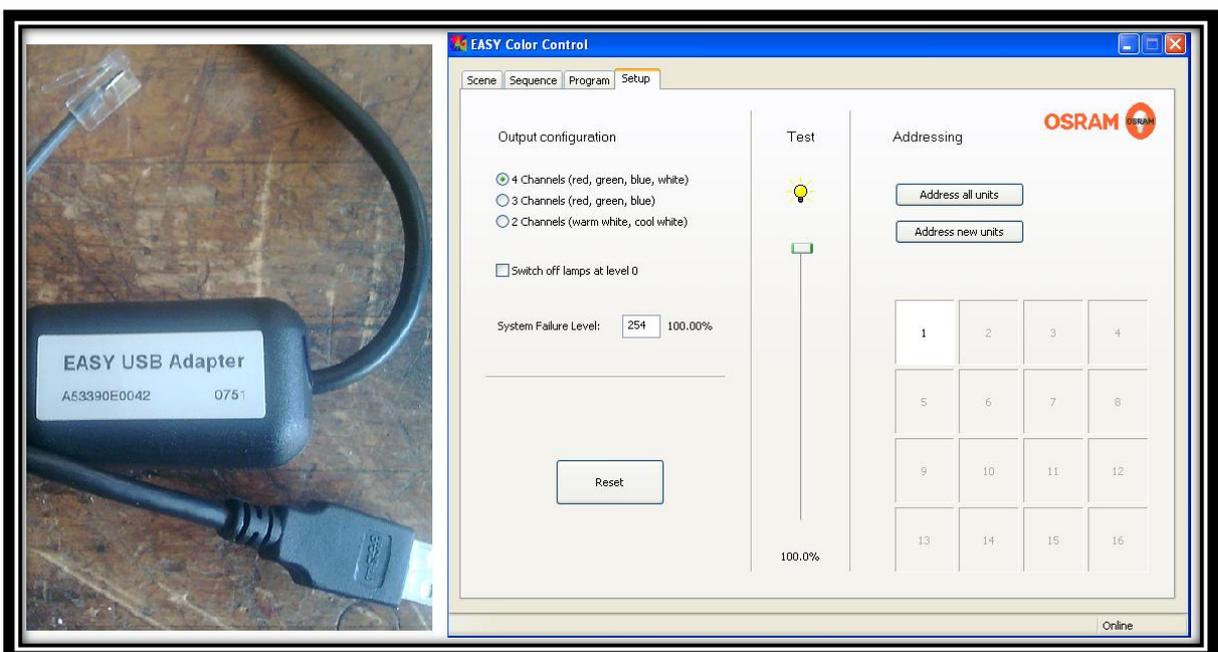

Figure 4.15: USB / RJ 11 adapter and a screenshot of the software tool "EASY Color Control" tested during the project.

The name of the software tool already indicates that its main purpose is color control, and not simply office lighting control. As a matter of fact, EASY Color Control is capable to drive not only white fluorescent tubes of different color temperatures, but also colored fluorescent tubes, colored LEDs as well as white LEDs. It is however possible to use the tool for simple switching and dimming actions, as well as for the definition of various lighting scenarios. The main advantage of this type of lighting control in terms of comfort is that the occupants can easily switch "on / off" and dim the two Tulux ZEN3 luminaires via their PCs. We experienced, however, two important drawbacks. First of all, the driver for the USB adapter caused significant problems under Windows Vista; this is of course not acceptable for such an important building service as office lighting. In addition to that, the EASY Color Control tool might be appropriate for managing complex color changes, sequences or daylight imitations: it was simply oversized for our scope and confusing. Switching and dimming of only two white fluorescent tubes is simply not as straightforward as it should be to represent a real alternative to the previously introduced remote control.

The third possibility for controlling the two Tulux Zen 3 luminaires that has been evaluated during the Green Lighting project is the use of the ECGs' "Touch Dim" function. This function makes it possible to switch and dim the light sources without the use of an additional DALI control unit (such as the DALI Easy II). Figure 4.16 shows the wiring diagram for this solution in our specific test office setting.
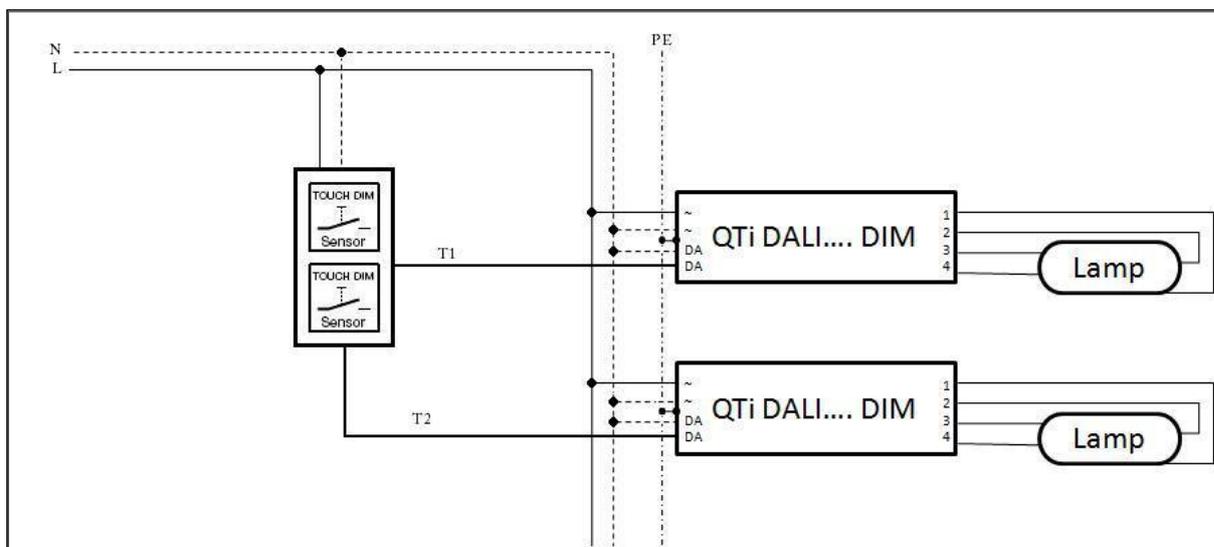
4.16: Wiring diagram of the test office setting when the "Touch Dim" function is used instead of a DALI controller.

Simple hand switches or electric push buttons (see Figure 4.17) can be used as "Touch Dim Sensors". The ECGs, as well as the sensors, are connected with the 240V power supply. One of each ECG's DALI inputs is connected to the neutral conductor of the 240V power supply, the other one is connected to one of the "Touch Dim Sensors" (via the T1 or T2 lines, respectively). The T1 and T2 lines are connected to power once the "Touch Dim Sensors" are pushed. Short pushing (i.e. less than 1s) causes switching (on or off) and long pushing (i.e. longer 1s) causes dimming (alternatively dimming towards higher or lower light flux).

Figure 4.17: Push buttons used in the scenario involving the "Touch Dim"-function (see Figure 4.16).

The major advantages of this technical solution is that no additional DALI control unit is needed and that the handling of the switches and the associated actions on the luminaires are extremely straight-forward. One possible drawback of the solution is the fact that the switches are not necessarily located within easy reach of the office occupants. However, this might not be a problem since the existing light switches within the LESO building are all installed next to the doors (i.e. out of reach for most occupants). This fact is, nevertheless, not causing major annoyances to the occupants (see Section 2.2).

We have therefore opted for the simple, straight-forward and cost-effective "Touch Dim Sensor"-solution using the two push buttons illustrated in Figure 4.17.

Figure 4.18 shows a measured dimming curve for this installation. The latter was determined by placing a luxmeter on one of the office room's individual workspaces (see Figure 4.6) and by then gradually dimming the light from a power consumption of 100% (corresponding to 62 W) down to 0% while making continuous luxmeter readings.
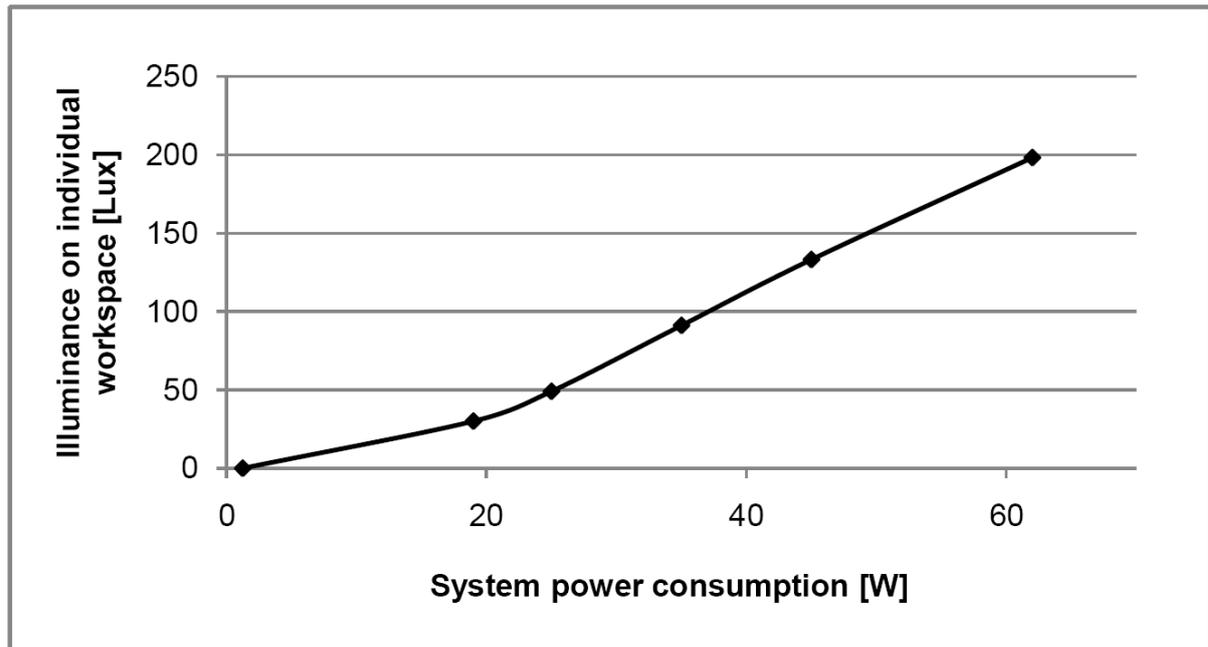
Figure 4.18: Measured dimming curve for the installation involving the "Touch Dim"-function (see Figure 4.16).

It can be seen from the resulting "Illuminance vs. Power"-plot that the decrease in illuminance is quasi-linear from 62 W down to approximately 20 W. It is also interesting to note that the illuminance curve does not intersect with the x-axis at 0 W. This shows that the ECGs consume electricity even when the lamps are switched off. This standby-power was measured: it is equal to 1.25 W for both ECGs.

4.4 System Validation and Post-Occupancy Evaluation

After the installation presented in Section 4.3 was completed, the average illuminance obtained on the workplane with the 3.9 W/m^2-lighting system was measured during night-time: an average illuminance of 286 Lux was determined on the workplane. The real value is thus 35% higher than the simulated value; due to this surprising result, we have also measured the average illuminance obtained on the workplane with the 4.5 W/m^2-lighting design switched on. An average illuminance of 234 Lux instead of the previously simulated 178 Lux was observed, which corresponds to a positive difference of 31% compared to the initial simulations.

The low values observed during the first simulation runs presented in Section 4.2 were due to the absence of furniture. Adding simply the four tables situated in the real office to our simulation yields already much closer simulation values. Figure 4.19 shows the results in terms of average illuminances and uniformities for this optimized computer model.
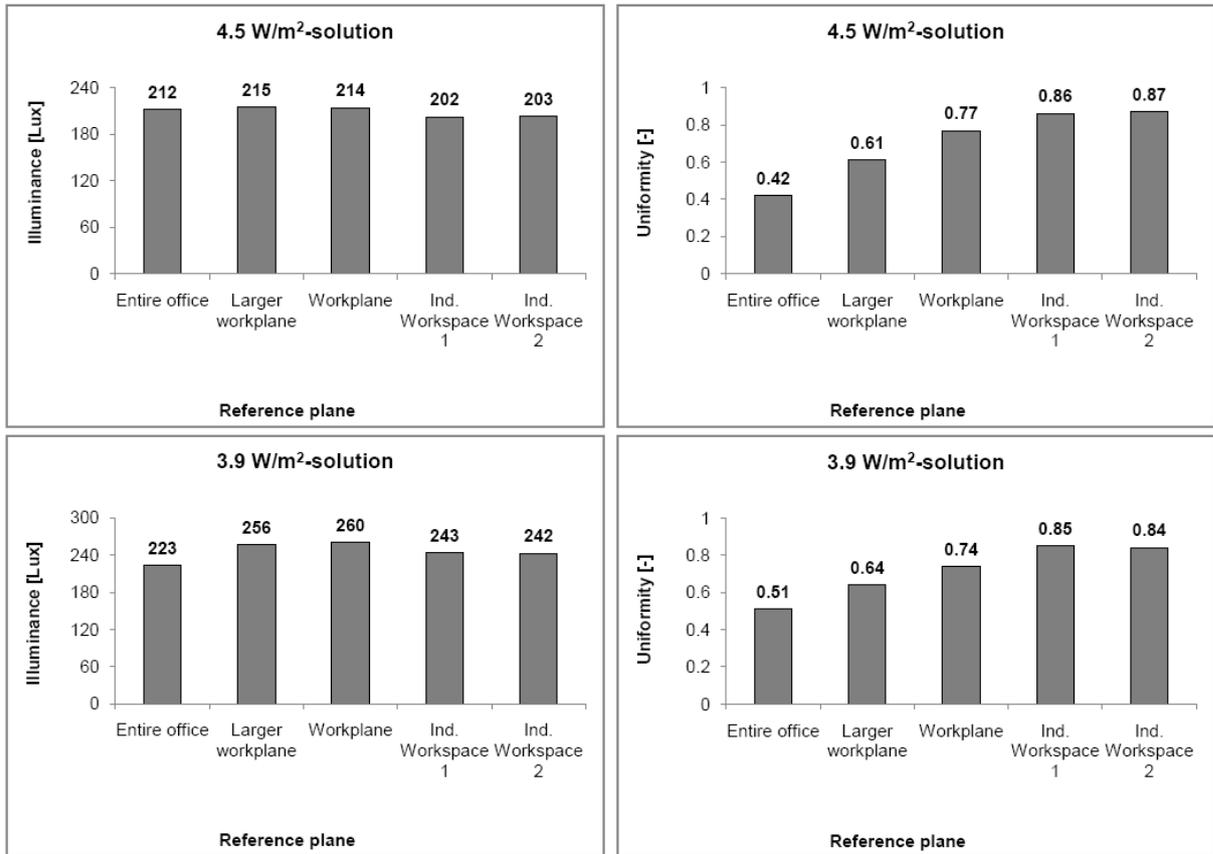
4.19: Results for the two lighting solutions in terms of average illuminances and uniformities for the optimized computer model.

These results reinforce the assumptions and conclusions of Section 4.1: initial simulation runs with a basic room model showed that that it would be possible to reduce the "Best practice" LPD from the current 4.5 W/m^2 value down to 3.9 W/m^2 or even 3 W/m^2 without significant deterioration of visual comfort.

However, these assumptions are still mainly based on predictions of illuminances and uniformities for different horizontal reference planes. To get a realistic assessment of how acceptable the more energy-efficient lighting designs are in reality, POEs with human subjects are mandatory. Hence, we have carried out a first study in the test office, during which 20 persons were asked to perform various tasks at a workplace situated in the office.

The workplace is shown in Figure 4.20. The subjects were young and healthy males and females (10 males, 10 females) with an academic background. Their average age was 23.7 years with a standard deviation of 3.5 years. The tests took part in evenings (external darkness) from April to May 2008.

Figure 4.20: Workplace used during our study in the test office room.

During each test session, the test persons' alertness was monitored using the Karolinska Sleepiness Scale (KSS). It is a subjective test during which the persons have to state their actual alertness on a 9-stage scale going from "extremely alert" (= 1) to "very sleepy, great effort to keep awake, fighting sleep" (= 9). The KSS was validated against EEG data by Åkerstedt and Gillberg in 1990 [Åkerstedt and Gillberg, 2009]. Table 4.1 gives an overview of the corresponding scale, the original ratings, as well as the translated French ratings used during our study.

Table 4.1 : Overview of the Karolinska Sleepiness Scale (KSS).

Value	Original rating	French rating
1	extremely alert	extrêmement alerte
2	very alert	très alerte
3	alert	alerte
4	rather alert	assez alerte
5	neither alert nor sleepy	ni alerte ni somnolent
6	some signs of sleepiness	signes de somnolence
7	sleepy, no effort to stay awake	somnolent, mais reste éveillé sans effort
8	sleepy, some effort to stay awake	somnolent, efforts pour rester éveillé
9	very sleepy, great effort to keep awake, fighting sleep	très somnolent, gros efforts pour rester éveillé, lutte contre le sommeil

One main objective of the study was to test the influence of the two different lighting designs (4.5 W/m^2 – solution and 3.9 W/m^2 – solution) on the subjects' performance during a *Computer based task*. For this purpose, the "Freiburg Visual Acuity & Contrast Test" (FrACT) [Bach, 1996] has been used. It allows to determine a person's visual acuity and contrast threshold through correct recognition of Landolt-rings on a PC screen. The computerized test can be downloaded free of charge on www.michaelbach.de/fract.

We have used two different methods to assess the occupants' visual performance for each of the two lighting conditions. The first method consisted of showing the subject a sequence of 36 Landolt rings of different size. The person had to determine the orientation of the ring and give the appropriate answer via the PC's keyboard as quickly as possible. Figure 4.21 illustrates this test.
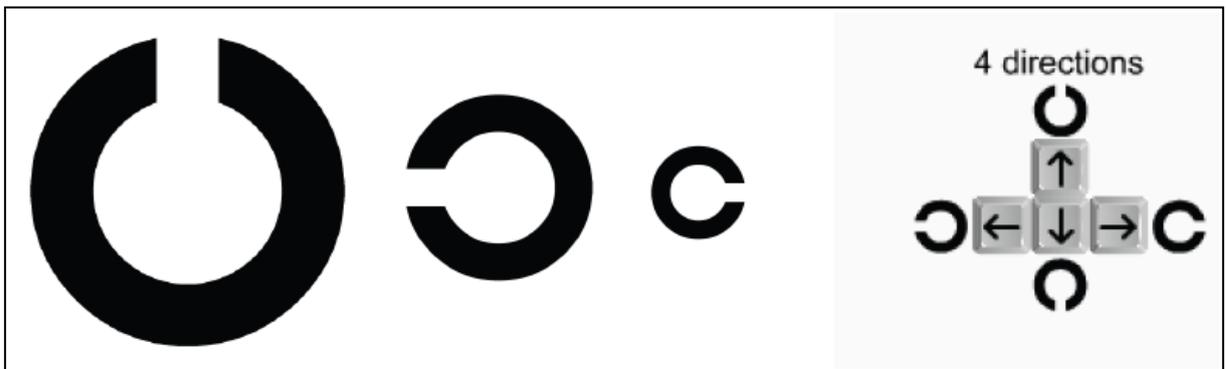

Figure 4.21: Acuity-part of the FrACT used during the study.

Each participant repeated this "acuity" -task three times under each lighting condition. After each sequence (36 Landolt rings), the participant took a short break which was used to store the results of the test (e.g. correct answers, response time per ring) in an Excel spreadsheet. For each sequence of 36 rings, the performance indicator η_{perf} was determined as follows:

$$\eta_{perf} = \frac{n_{correct}}{\tau_{sequence}}$$
(Equation 6)

where $n_{correct}$ stands for the total number of correctly identified Landolt rings per sequence and $\tau_{sequence}$ stands for the total duration of the sequence.

Using the FrACT to determine a person's contrast threshold is another possible way to assess visual performance. Instead of looking at Landolt rings of different size, the contrast between the ring and the screen background is modified during the test: this "contrast"-test is illustrated in Figure 4.22.

Figure 4.22: Contrast-part of the FrACT used during the study.

Yet again, each subject performed three sequences of this "contrast"-task of 36 Landolt rings for each of the two lighting scenarios.

Another main objective of this study was to test the influence of the two different lighting designs on the subjects' performance during a *paper based task*. For this purpose, we have used a test suggested by Courret and Scartezzini [Courret and Scartezzini,1999] in 1999. Yet again, Landolt rings are used during this test: the study participants receive a piece of white paper on which 96 Landolt rings are printed in clear grey. They are asked to determine, as quickly as possible and without writing on the paper, the correct orientations of the 96 rings by writing down the number of counted rings for all four possible orientations (open on top, open on bottom, open left, open right). The contrast between the paper and the grey color of the rings is very weak which makes this quite a difficult task; the test is shown in Figure 4.23.

Compter les anneaux en fonction de leur orientation
et inscrire ci-dessous le nombre trouvé pour chaque catégorie
(Effectuez cet exercice le plus rapidement possible
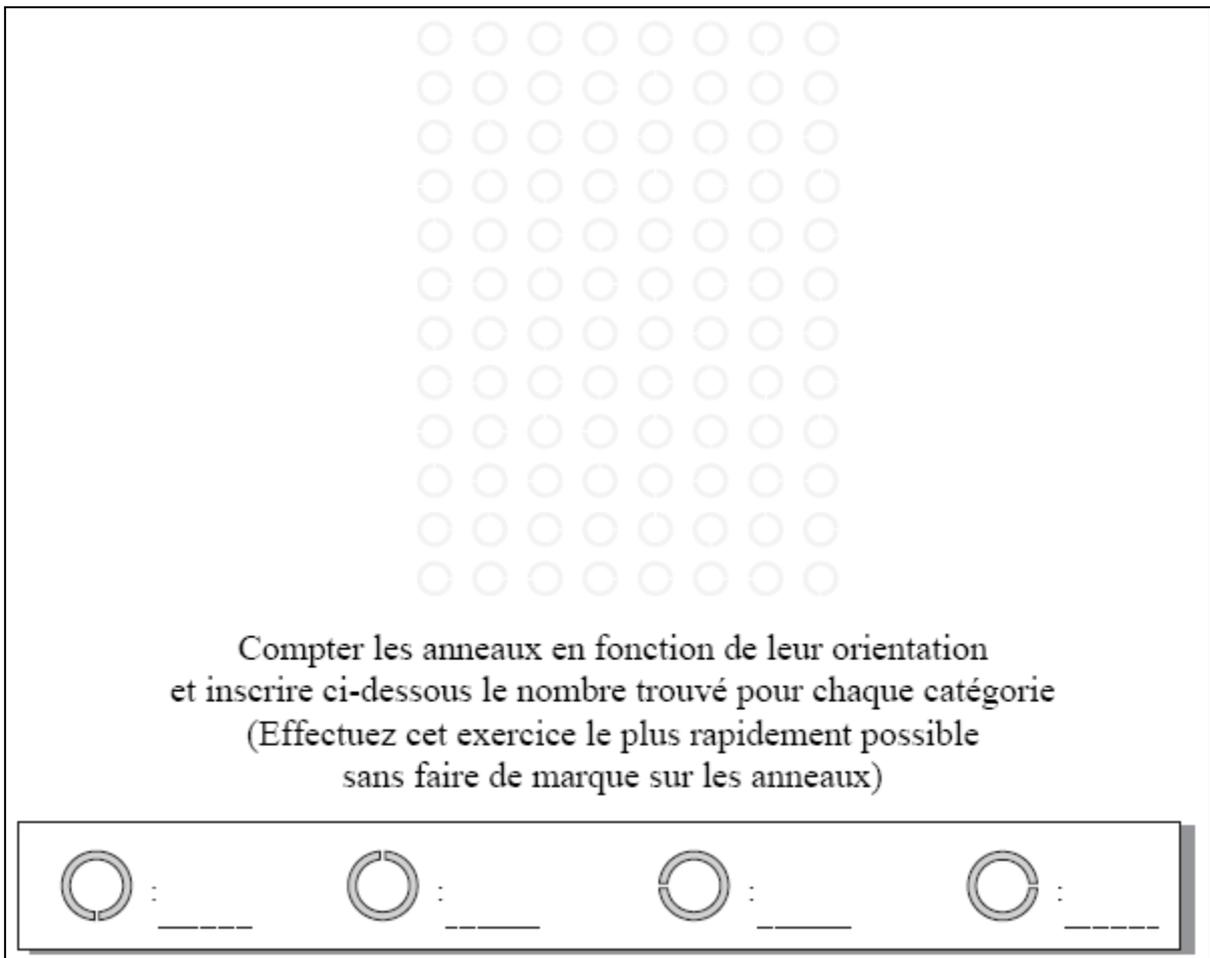sans faire de marque sur les anneaux)

Figure 4.23 : Paper-based Landolt ring task as suggested by Courret.

We have used two different versions of this visual performance test (i.e. with different ring orientations) in order to avoid any bias from people who remember the number of rings previously counted during the first lighting scenario while they are doing the test under the second lighting scenario.

In addition to the alertness assessments, the computer-based tasks and the paper-based tasks, the test persons' subjective visual comfort was also assessed. This was done using a questionnaire similar to the modified OLS presented in Section 2.

After arriving at the laboratory at the scheduled appointment time, each participant was offered a quick tour around the building: this typically took between 5 and 10 minutes. Then, a quick introduction concerning the study was given, questions were answered and study participants were offered to use the bathrooms. After that, the visual performance tests began. Figure 4.24 shows the study schedule.
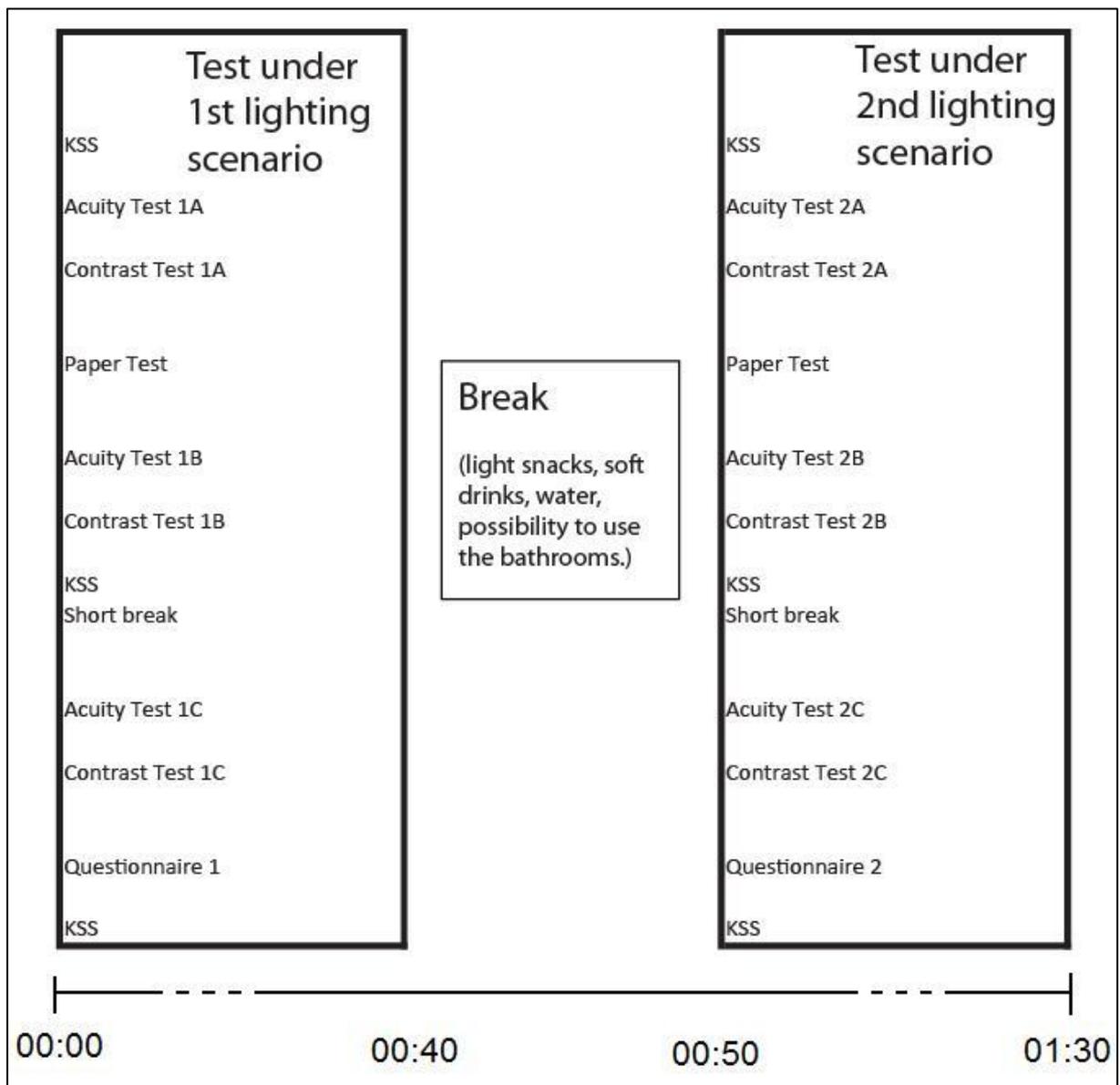

Figure 4.24: Study schedule.

Each subject was tested once under the 4.5 W/m^2-condition and once under the 3.9 W/m^2-condition. Half of the participants started under one condition, the second half under the other condition. In the beginning of each session, the participants filled out a KSS-test. Then, they performed a computer-based acuity-test and a computer-based contrast-test

(determining the correct direction of 36 Landolt-rings in both cases). After that, the paper-based task (see Figure 4.23) was carried out. The latter was followed by another sequence of acuity- and contrast-tests, a KSS-test and a short break during which participants were shown a humorous video clip (for relaxing reasons). Participants then took a third sequence of acuity- and contrast-tests and filled out the questionnaire for subjective visual comfort assessment. Each session ended with a third KSS-test. The whole session took approximately 40 minutes. Between the two sessions, the lighting scenario inside the office room had to be modified. Meanwhile, the occupants took a break of approximately 10 minutes during which they were offered light snacks, soft drinks and water. They were also allowed to use the bathrooms. Then, the second session started. The only difference between the two sessions was the fact that the questionnaires for subjective visual comfort assessment filled out by the participants at the end of each session were slightly different: while the first one only contained 16 lighting-related questions, the second one had an additional section with general questions (e.g. age, normal working hours, normal working locations).

Figure 4.25 shows the participants' alertness monitored by means of the KSS-tests throughout the study. The dotted line shows the evolution of the participants' average alertness over the duration of the entire experiment (i.e. 90 minutes). The average alertness evolution during the session where the 4.5 W/m^2-solution was tested (reference) is plotted as a solid line, the alertness evolution during the 3.9 W/m^2 (test) as a dashed line. It is obvious that there were no significant changes in the average alertness, neither over the entire study, nor over one of the two sessions. The average alertness was always situated between "rather alert" and "alert". Nevertheless, one could get the impression that a slight decrease in alertness occurred (i.e. an increase of the average KSS rating) during the "reference"-sessions and a very slight increase of alertness (i.e. a decrease of the average KSS rating) during the "test"-sessions. These small differences are, however, not statistically significant. The small KSS rating variations over the entire experiment are also not statistically significant. This means that there is a considerable probability that the variations observed in Figure 4.25 have occurred by chance. It therefore makes sense to assume that the participants' alertness did not change throughout the study and that it is not possible to distinguish the two lighting scenarios regarding the participants' alertness.
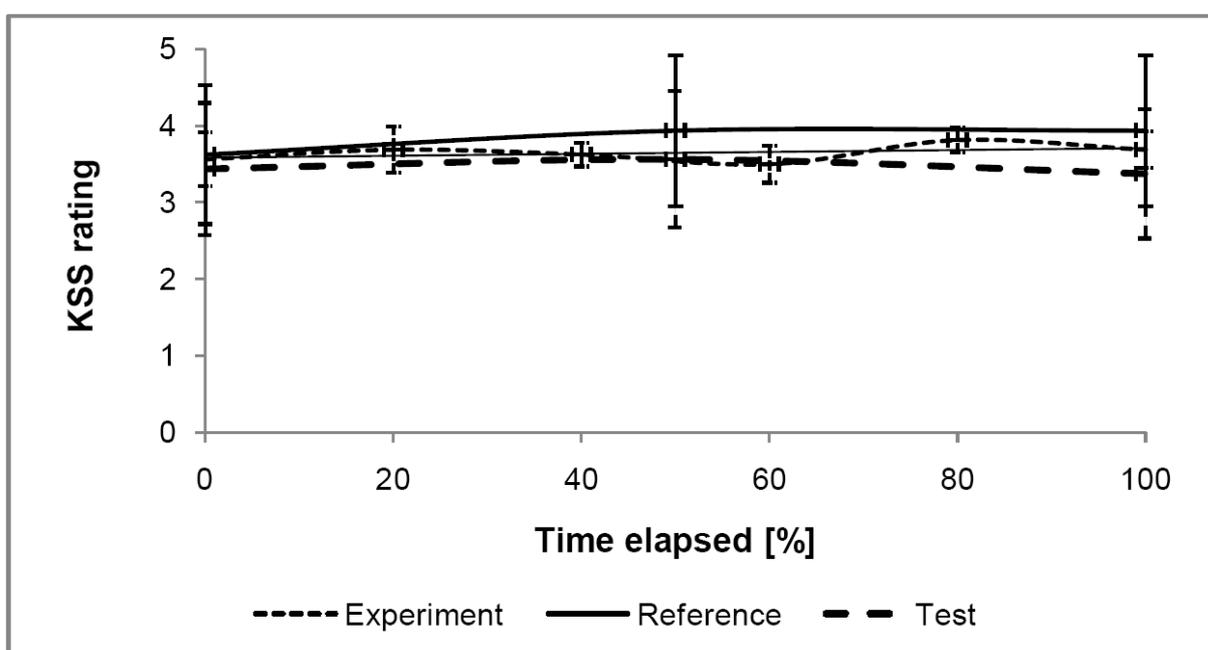

Figure 4.25: Evolution of the subjects' average KSS ratings over the duration of the study.

Figure 4.26 gives an overview of the results obtained during the computer-based tasks. The average performance indicator η_{perf} of all "acuity"-tests is shown in Figure 4.26 (left) for the two different lighting conditions. For both of them, the average performance indicator is close to 0.9 correct decisions per second (standard deviations of approximately +/− 3% in both cases). The small observed difference is not statistically significant (t-Test performed on test data yields a p-value of 0.1611).
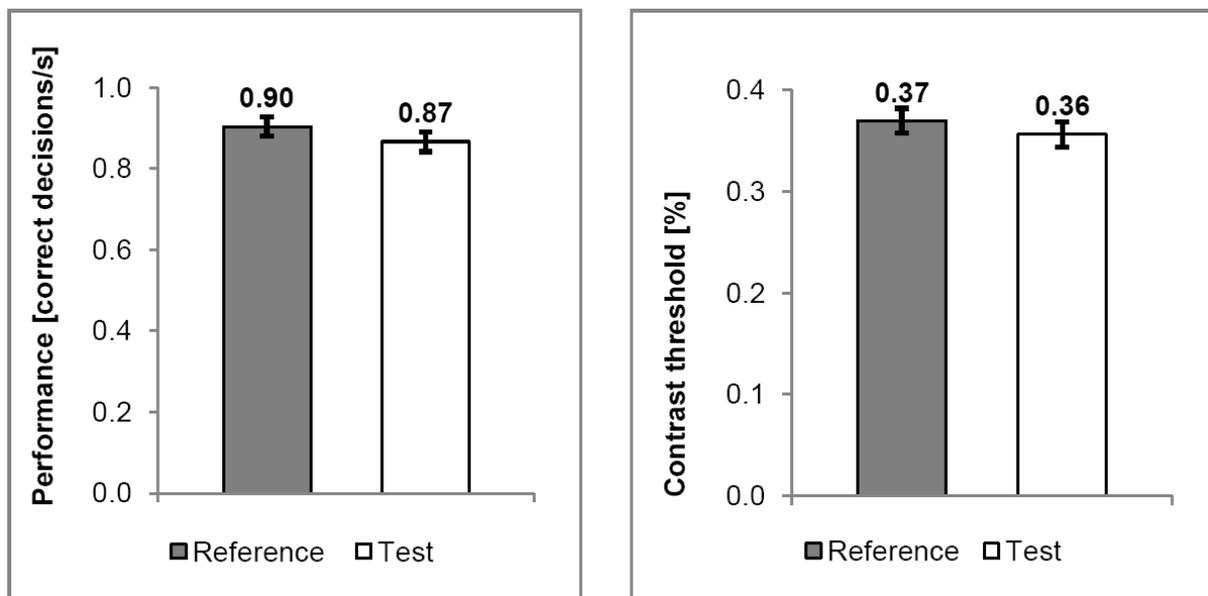

Figure 4.26: Overview of the results obtained during the computer-based tasks.

Figure 4.26 (right) shows a comparison of the average contrast thresholds obtained during the "contrast"-tests for the two lighting scenarios. It appears that the study participants performed slightly better under the 3.9 W/m^2-solution, but the small difference could, once more, not be shown to be statistically significant (t-Test performed on test data yields a p-value of 0.1580).

It can be concluded that there was no measurable influence of the lighting scenario on the study participants' performance during the computer-based tasks. In other words: the participants did not perform better or worse on the computer task under one or the other lighting scenario.

Figure 4.27 shows the results of the paper-based task for the two different lighting conditions. The average number of mistakes per ring orientation is shown in Figure 4.27 (left). One can observe that the subjects made more mistakes under the "Best-practice"-lighting "reference"-lighting (4.5 W/m^2, considered as the reference case) than under the "test"-lighting (3.9 W/m^2). This is even more obvious when looking Figure 4.27 (right): the latter shows the average (over 20 participants) number of mistakes for the sum of all Landolt-ring orientations. Under the "reference"-lighting, the participants got in average 24.95 out of 96 Landolt-ring orientations wrong, while they made only an average of 18.68 mistakes under the "test"-lighting. The figure also shows that the average study participant made an average of 6.24 mistakes per ring orientation under the "reference"-lighting and only an average of 4.67 mistakes per ring orientation under the "test"-lighting. Both differences displayed in Figure 27 (right) are statistically significant (Student's t-Tests performed on test data yielded p-values of 0.0321 and 0.0095, respectively).
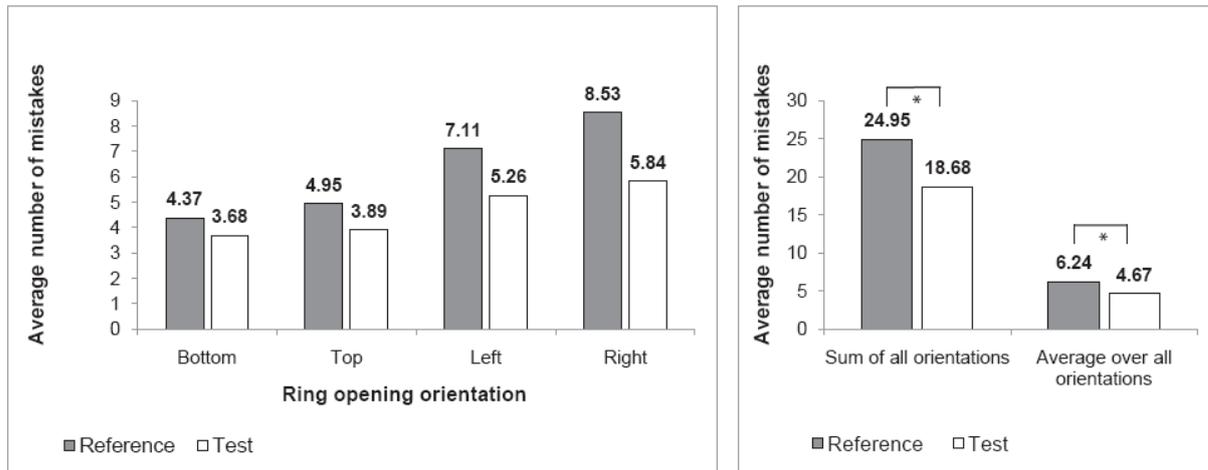
Figure 4.27: Results of the paper-based task for the two different lighting conditions.

It can also be observed that the average number of mistakes increases for both "reference"- and "test"-conditions from "bottom" to "right". Taken into account the layout of the paper-based task (see Figure 4.23), it seems probable that most subjects first counted the rings oriented towards the bottom, then those oriented towards the top, followed by those oriented towards the left and finally those oriented towards the right. If this assumption is true, than Figure 4.27 (left) visualizes how difficult this paper-based task was for the participants and how they made more and more mistakes over the duration of the task. The increase of mistakes can even be quantified: under the 4.5 W/m^2-condition, the average number of mistakes increased by 95%, while there was only an increase of 59% under the 3.9 W/m^2-condition.

In summary, this analysis of the paper-based task shows, that the subjects performed on average better under the new 3.9 W/m^2-condition (Test cas) than under the "Best practice" 4.5 W/m^2 condition (Reference case). The better performance is most likely due to higher workplane illuminance and a brighter room achieved under the 3.9 W/m^2 lighting scenario.

Figure 4.28 now shows the results of the subjective visual comfort assessment. Nineteen out of 20 study participants have filled out the corresponding questionnaires.
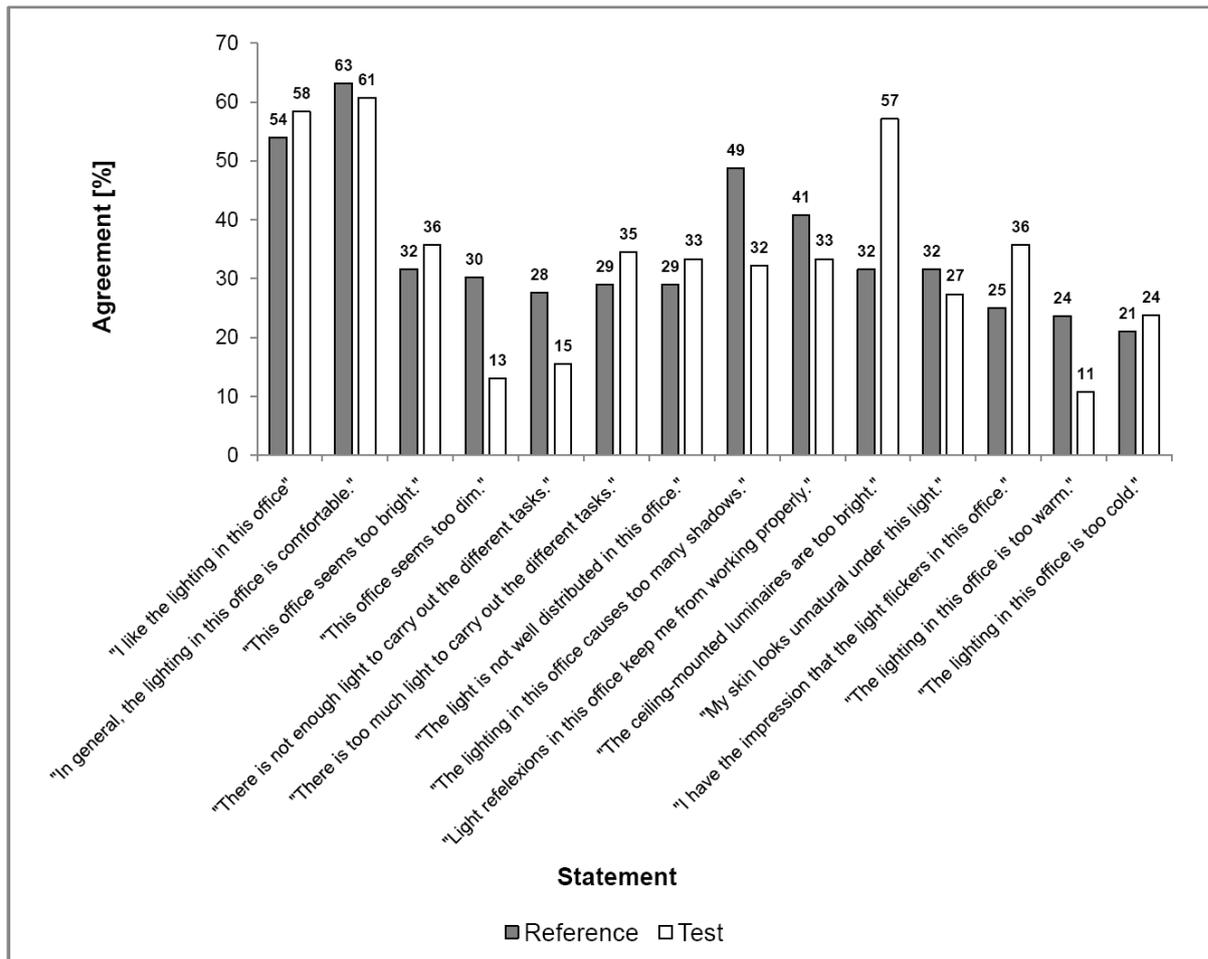
Figure 4.28: Results of the subjective visual comfort assessment.

The statement "In general, the lighting in this office is comfortable." scored agreement values of 63% for the 4.5 W/m^2-condition and 61% for the 3.9 W/m^2-condition. These values are slightly lower than the typical values described by Akashi and Boyce [Akashi and Boyce, 2006]. This is not surprising at all because our experiments took place during external darkness whereas the values described by Akashi and Boyce are most likely to describe agreements tested during normal office hours (with at least some daylight and its associated positive effects). We can therefore assume that the two tested lighting scenarios are comparable to lighting conditions in other office rooms. It might seem surprising that the "test"-lighting scores better agreement values in statement S1 than the "reference"-lighting and that this trend is inversed in statement S2. However, the small differences in the average agreements to these two questions are not statistically relevant. There is thus a considerable probability that they have occurred by chance. As a matter of fact, only the differences in statements S4 ("This office seems too dim.") and statement S10 ("The ceiling-mounted luminaires are too bright.") could be shown to be statistically significant (Student's t-Tests performed on test data yielded p-values of 0.0356 and 0.0109, respectively). Nevertheless, it seems somewhat surprising that a significant difference between the two lighting designs for statement S4 ("This office seems too dim.") and none for statement S5 ("There is not enough light to carry out the different tasks.") were found. It is possible that the absence of significance is in many cases the result of the small number of study participants rather than the result of an absence of a difference. It therefore makes sense to take a closer look at various statements where a large difference between the two lighting designs has occurred, even if some are not statistically significant.

Figure 4.29 shows the differences between the "reference"- and the "test"-lighting for the statements S1 to S14. A negative value means that the "test"-lighting performs worse than

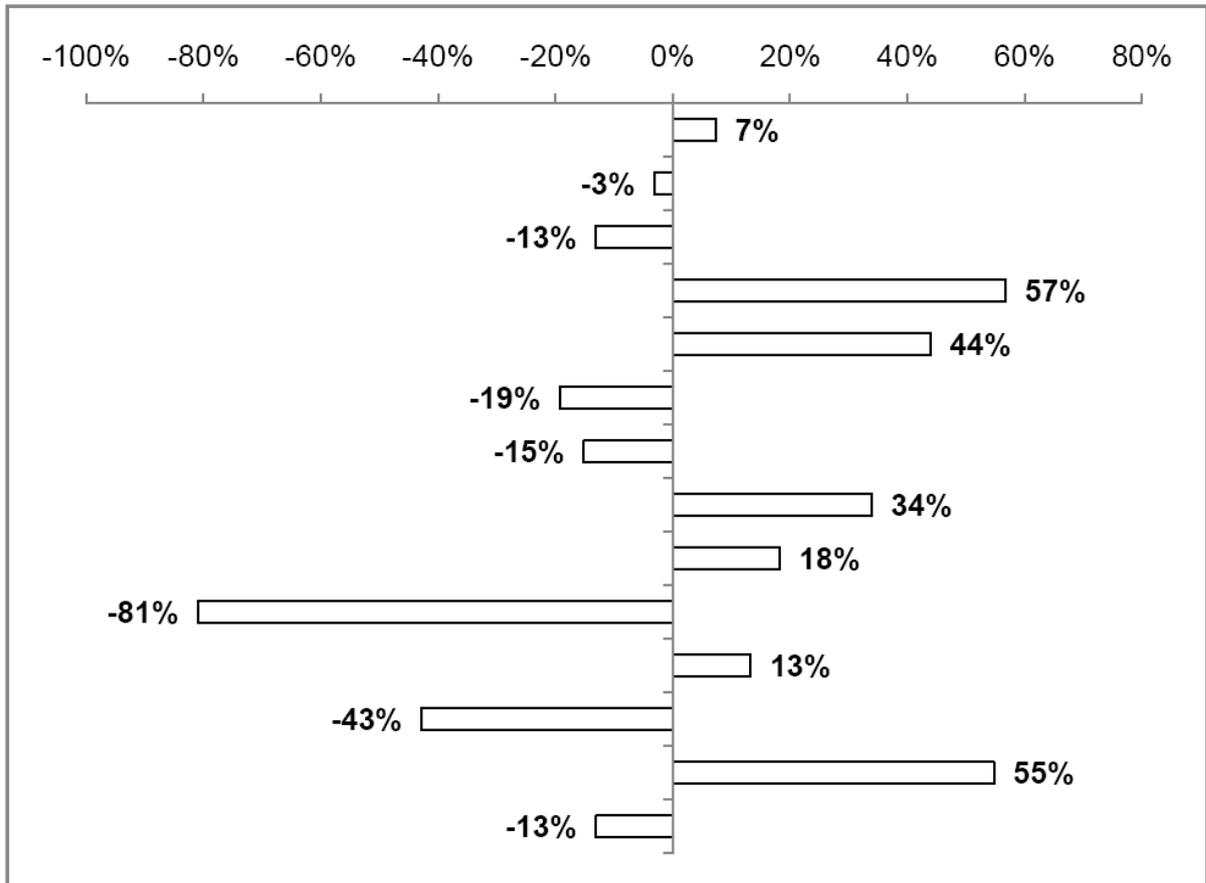the "reference"-lighting under this specific viewing angle, a positive value corresponds to an enhancement.

Figure 4.29: Differences between the "reference"- and the "test"-lighting for the statements S1 to S14.

If we take into account only those statements where a difference of +/- 20% is observed, we find an enhancement for the statements S4, S5, S8 and S13 and deterioration for the statements S10 and S12. The facts that the new 3.9 W/m2-condition creates higher illuminances on the workplane (S5) and makes the room in general appear brighter and less gloomy (S4, S8 and S13) are perceived positively, whereas the aggressiveness (S12) and especially the increased luminance of the luminaires (S10) are perceived negatively.

Figure 4.30 shows an additional result of the subjective visual comfort assessment. In addition to the 18 statements listed above, the study participants were asked to state the maximum amount of time per day during which they could imagine themselves working under the given lighting condition. The results suggest a maximum working time that is higher for the 3.9 W/m^2-condition than for the 4.5 W/m^2-condition.
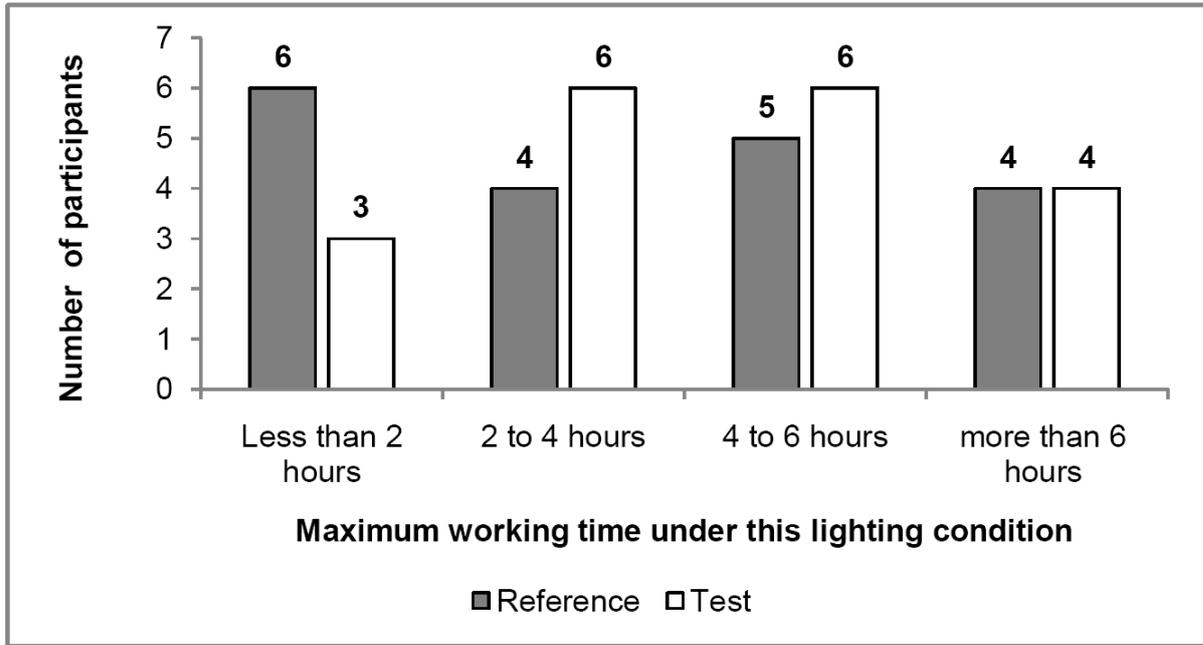
Figure 4.30: Maximum working time under each lighting scenario as indicated by the subjects.

At the end of the experiment, each participant was asked whether he or she preferred the 4.5 W/m^2-condition or the 3.9 W/m^2-condition. Figure 4.31 shows the participants' answers to this question.
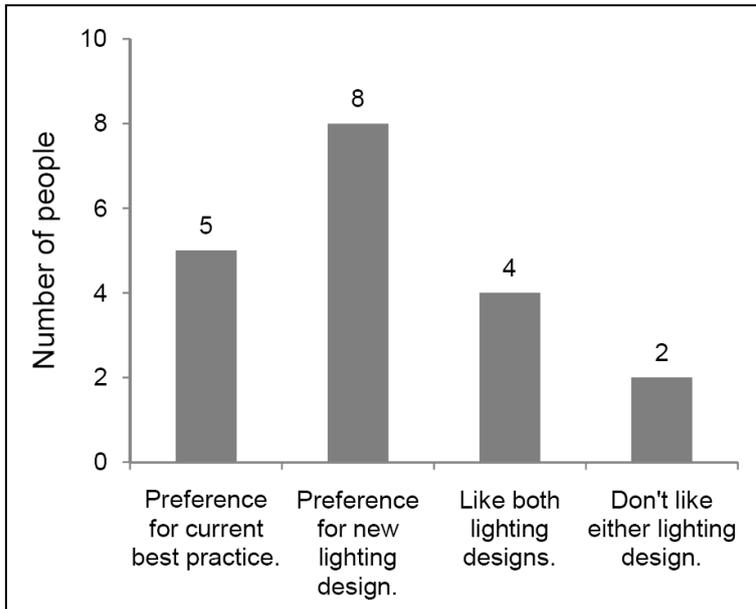
Figure 4.31: Study participants' subjective preferences.

We can observe that five (out of 19) participants had a preference for the current lighting design, whereas eight participants preferred the 3.9 W/m^2-condition; four participants liked both solutions equally well. Only two participants felt that neither of the two environments was comfortable enough.

The results of the subjective visual comfort assessment outlined in Figures 28 to 31 can be interpreted as follows: despite the higher luminaire luminance and the more "aggressive" lighting style, the participants slightly preferred the new 3.9 W/m^2 – lighting design over the old 4.5 W/m^2 – lighting design. It is moreover possible to say that occupant satisfaction under the 3.9 W/m^2-condition is not significantly worse than under the 4.5 W/m^2-condition.

4.5 Conclusion

The results of our tests on visual performance and subjective visual comfort under two different low-LPD lighting scenarios lead to several interesting conclusions. First of all, the results show that the two tested low-LPD lighting scenarios are comparable to usual lighting scenarios in other office rooms in terms of subjective visual comfort. We found average agreements with the statement "In general, the lighting in this office is comfortable." of 65% for our "Reference"-scenario (4.5 W/m^2) and 70% for our "Test"-scenario (3.9 W/m^2) using a 2-stage answering scale. Akashi and Boyce put forward a typical agreement of 69 % in US office buildings [Akashi and Boyce 2006]. The facts that the new "Test"-condition creates higher illuminances on the workplane and makes the room in general appear brighter and less gloomy were perceived positively by the study participants, whereas the increased luminance of the luminaires under this lighting scenario were perceived negatively. Overall, the study participants nevertheless preferred the "Test"-scenario over the "Reference"-scenario. In addition to that, their performance in our paper-based task was significantly better under the "Test"-lighting than under the "Reference"-lighting. This effect is most likely to be due to the higher workplane illuminances under the "Test"-lighting. This leads us to the conclusion that when working under artificial lighting conditions during a limited amount of time in the evening hours, the positive effects of elevated workplane illuminances are stronger than the negative effects of discomfort glare from luminaires. Another interesting finding of this study is the fact that no significant differences in the computer-based tasks under the two different lighting scenarios where found. This could of course indicate that the "Freiburg Visual Acuity & Contrast Test" (FrACT) [Bach, 1996] used during our study was inappropriate for our means. However, it also visualizes to what intent the lighting environment has a much smaller influence on the performance during computer work than on the performance during paper work.

In general, it can be concluded that energy-efficient lighting with LPDs of less than 5 W/m^2 is already achievable in today's office rooms without jeopardizing visual comfort and performance.

5   New lighting technologies

5.1   LED technology for indoor illumination

Over the last few years, light emitting diodes (LEDs) have witnessed a breathtaking development and have become widely available for various consumer products. Colored LEDs have introduced as a source for emergency and decorative lighting, as well as indicator lamps, traffic lights and automotive applications for example.

White LEDs are becoming more and more common for portable lighting solutions, such as torches or bicycle lights; they are unfortunately not yet widely used as light sources for general lighting, such as office lighting. There are two profoundly different methods for producing white light with LEDs. The first one consists of combining red, green and blue LED chips in the same package to produce white light. This type of white light is however not of good quality, persons with color deficiencies (i.e. color blinds) will not see the emitted light as white. The second method uses blue LEDs in combination with photoluminescent phosphors, much like in fluorescent tubes. In this way, a cool white light of better quality can be produced.

Coating blue LEDs with quantum dots that emit white light in response to the blue light radiated by the LED is a way to produce a warmer, yellowish-white light similar to that produced by incandescent bulbs instead of the bluish light described above [Gabrani et al., 2006]. Using LEDs with their emission shifted towards the ultraviolet part of the electromagnetic spectrum in combination with fluorescent coatings is yet another possible way to produce white light from LEDs.

5.2   LED for ambient lighting

In the course of a student project carried out at EPFL in 2007, we have studied the impact of using white LEDs instead of conventional light sources in an office environment [Gabrani et al., 2006]. After identifying suitable LED products, we have used the RELUX Vision software tool for simulating energy-efficient lighting solutions based on LED technology for an office room. In particular, the use of white LED light sources in ceiling mounted spot luminaires (Altea LED Bianco 180 mm, manufactured by ARES S.R.L) has been considered (see Figure 5.1). Those luminaires were initially equipped with five white LEDs (1.2 W power consumption) and designed rather for decorative than for general lighting. In absence of specific LED luminaires for general lighting (during the year 2007), it was assumed that these luminaires could be used for this purpose by simply rising their light output flux.

Figure 5.1 : Altea LED Bianco 180 mm, manufactured by ARES S.R.L.

During the simulations, we have gradually increased the luminaires' output flux to luminous efficacies between 60 lm/W and 100 lm/W, corresponding to values achieved by the most advanced LED technology. Figures 5.2 to 5.4 show the resulting illuminance distributions. The illuminance distribution over the entire workplane and on the other reference planes introduced in Chapter 4 can be observed in the first figure. The source efficacy in this case is equal to 60 lm/W. Figures 5.3 and 5.4 show the simulation results with lamp efficacies of 80 lm/W and 100 lm/W, respectively, for the same room.
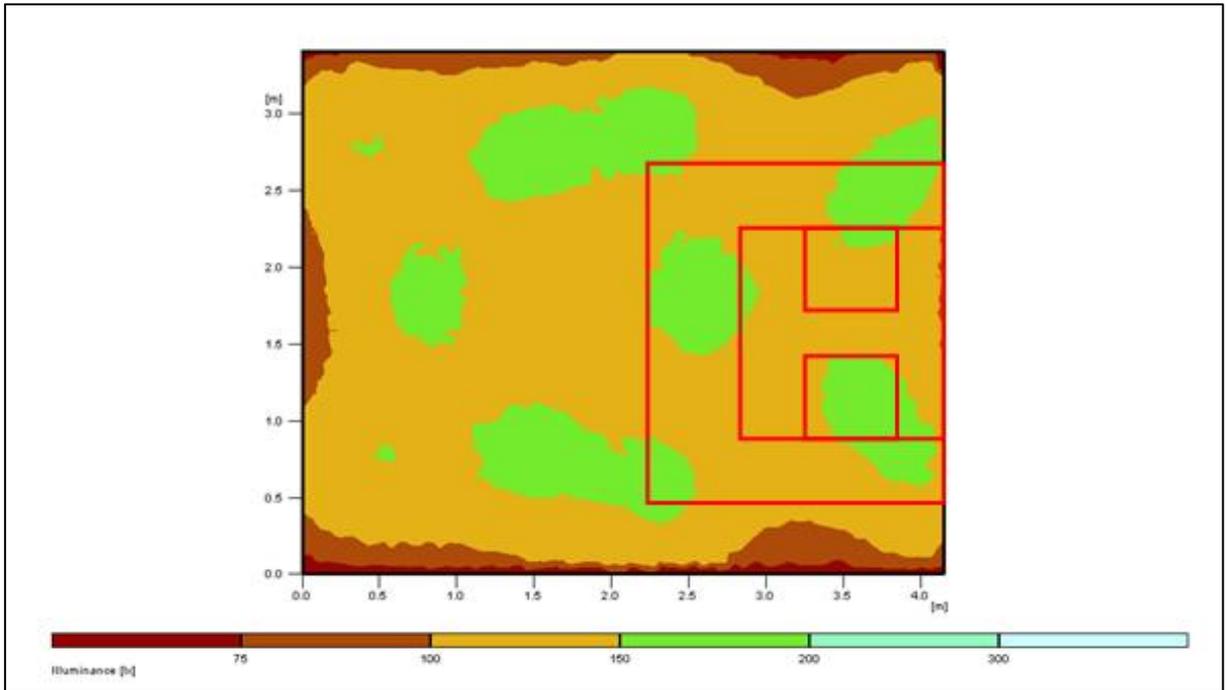
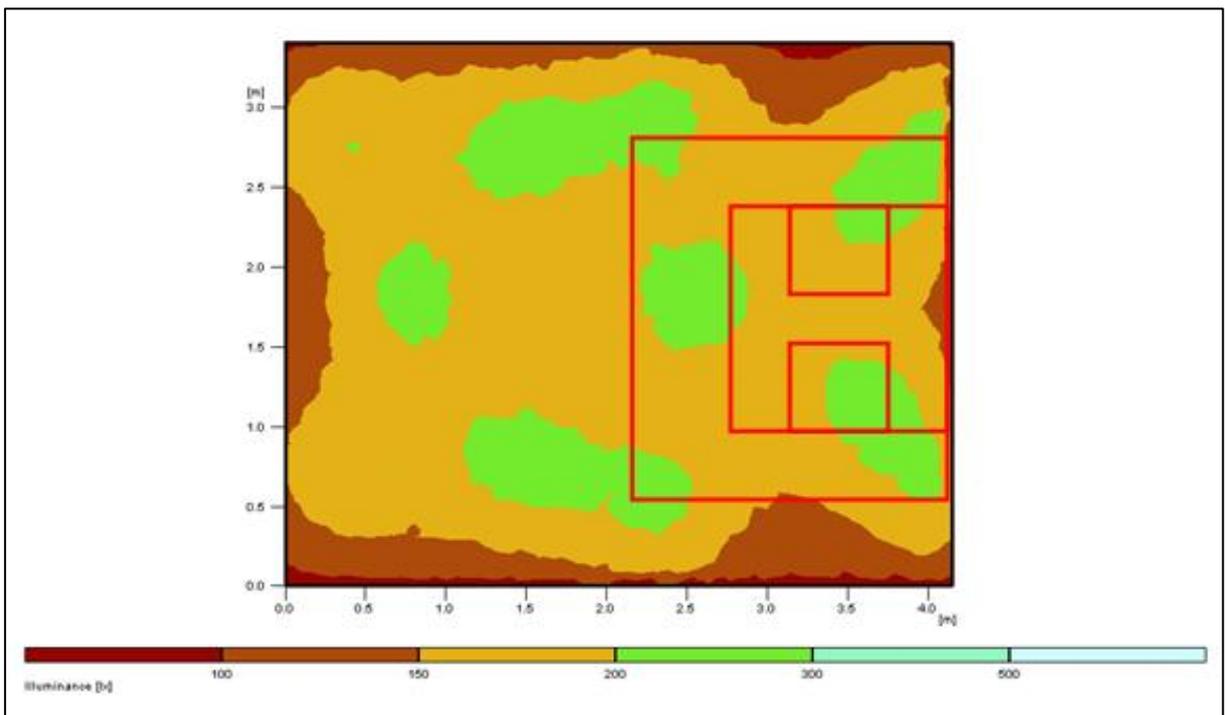**Figure 5.2 : Illuminance distribution in the office room for an LED luminous efficacy of 60 lm/W.**

Figure 5.3 : Illuminance distribution in the office room for an LED luminous efficacy of 80 lm/W.
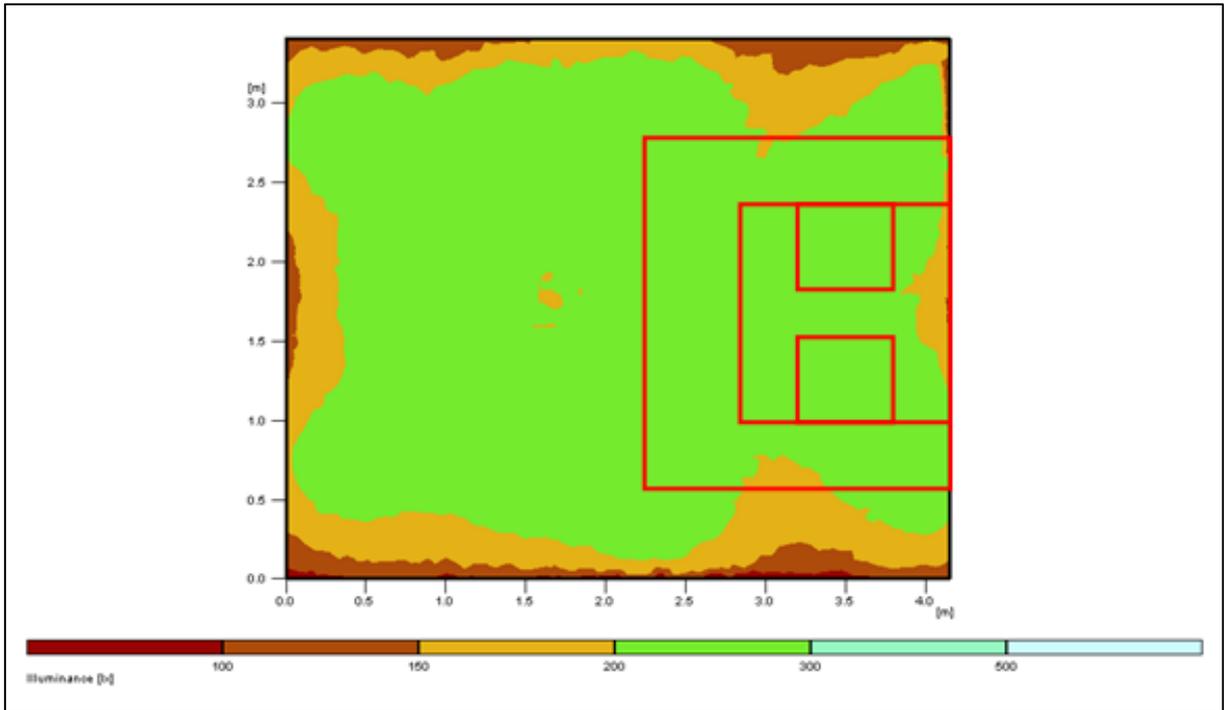
Figure 5.4: Illuminance distribution in the office room for an LED luminous efficacy of 100 lm/W.

The bar chart in Figure 5.5 shows the average illuminances on the different reference planes of the current installation, as well as those of the considered LED-simulations with efficacies ranging from 60 to 100 lm/W. The dependency between the average illuminances and the LED efficacies is quasi-linear. One can observe that the 80 lm/W and 100 lm/W LED-lighting solutions perform better than the current installation for all reference planes. The bar chart in Figure 5.6 shows the corresponding illuminance uniformities g1. One can observe that LEDs with an efficacy of 80 lm/W provide the best illuminance uniformities on the different reference planes. On most reference planes, uniformities achieved by the 100 lm/W LED-solution are slightly lower than those achieved by the 80 lm/W LED-solution. This leads to the conclusion that the best trade-off between average illuminance and uniformity for this particular situation is obtained for a lamp efficacy of 80 lm/W; it suggests that white LEDs would become a real alternative for the substitution of fluorescent tubes once they reach luminous efficacies of 80 lm/W. Other simulations, assuming an 80 lm/W lamp efficacy, were run in consequence.
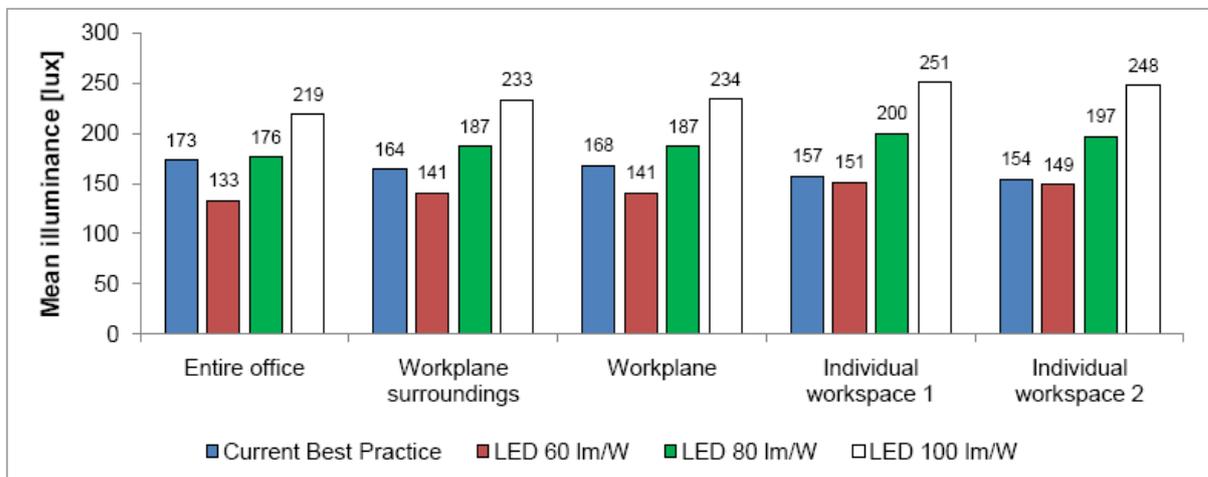

Figure 5.5 : Average illuminances on the different reference planes of the current installation and the considered LED-simulations with LED luminous efficacies ranging from 60 to 100 lm/W.
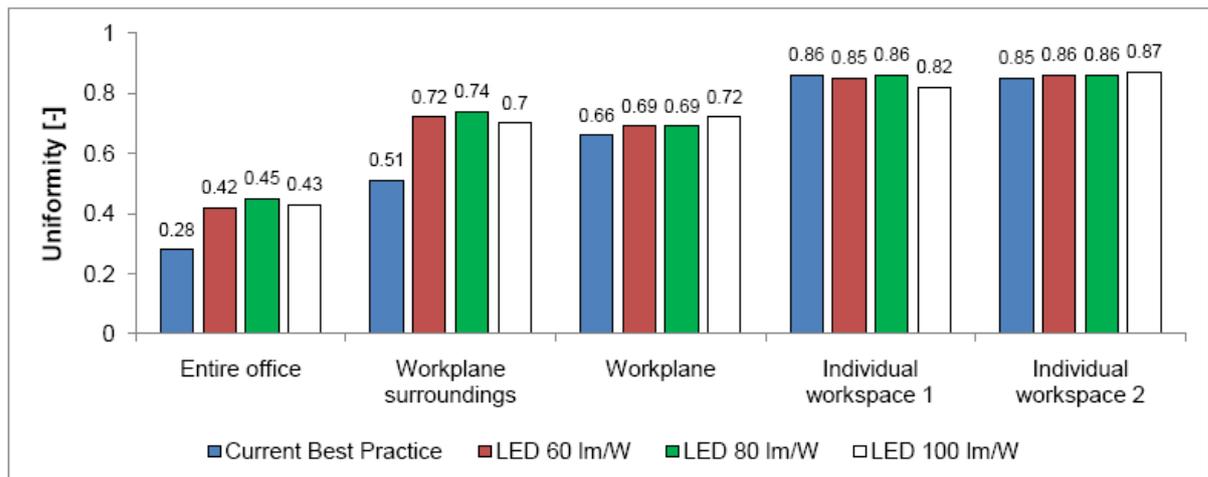
Figure 5.6: Average illuminance uniformities on the different reference planes of the current installation and the considered LED-simulations with LED luminous efficacies ranging from 60 to 100 lm/W.

The luminaires used during these simulations were identical to those used previously (Altea LED Bianco, 5 x 1.2 W); their number and positions were however modified with the aim of reducing lighting power density. Our reference for this set of simulations with lamp efficacies of 80 lm/W is the one already shown in Figure 5.3 ("Case 1").

Figure 5.7 illustrates an alternative design including 10 luminaires and the resulting illuminance distribution within the office room. The LPD in this case is 3.75 W/m^2, which is referred to as "Case 2".

Figure 5.7: First alternative lighting design including 10 luminaires. The LPD in this case is 3.75 W/m^2. This scenario is referred to as "Case 2".

"Case 3" is shown in Figure 5.8. Ten LED-luminaires were also used in this case, but the positions on the ceiling have been substantially modified. Eight of the 10 luminaires are not pointing directly downwards but are aligned in the directions indicated by the black arrows. One can observe that the illuminance distribution is very different to the one of "Case 2".
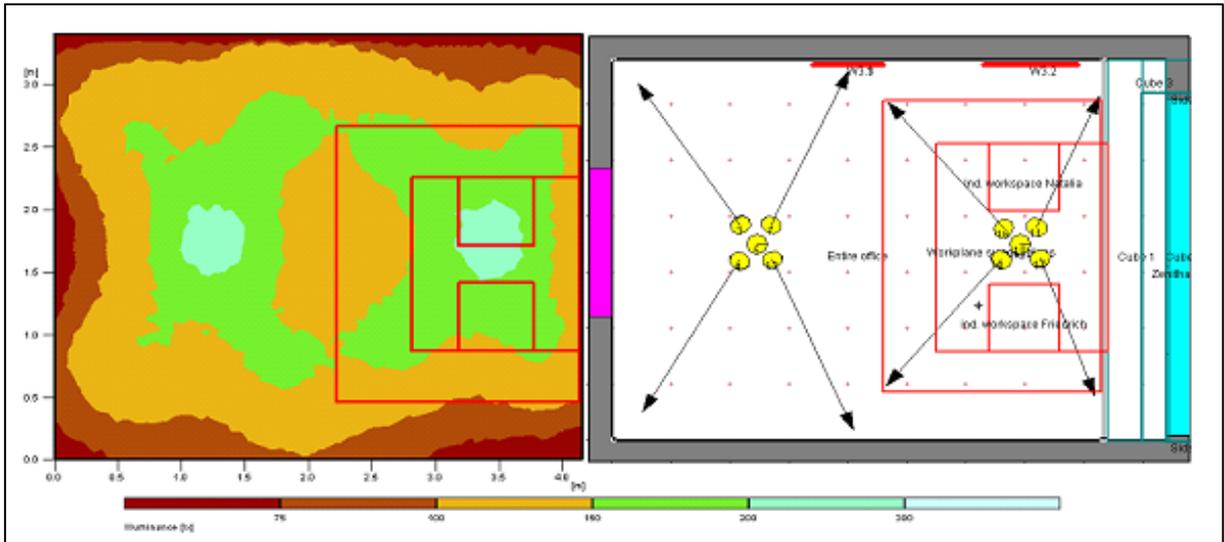
Figure 5.8: Second alternative lighting design including 10 luminaires. Luminaire positions are modified and not all luminaires are pointing downwards. The LPD in this case is 3.75 W/m^2. This scenario is referred to as "Case 3".

Figure 5.9 shows another configuration referred to as "Case 4". This installation is derived from "Case 3", but the two downwards-pointing LED-luminaires have been removed. This leads to an LPD of only 3 W/m^2.
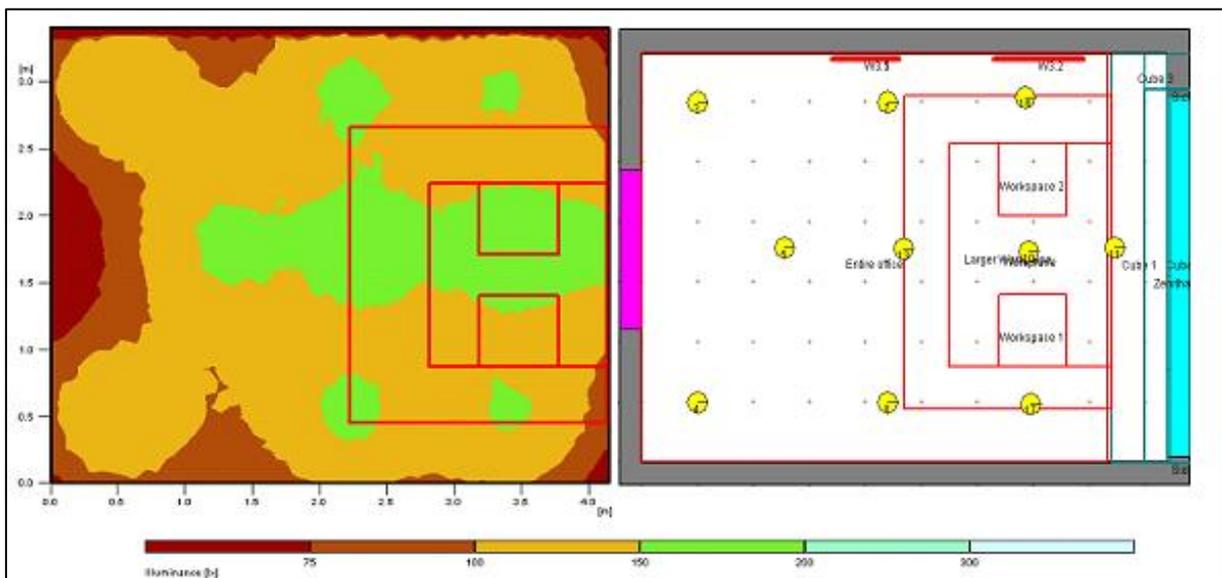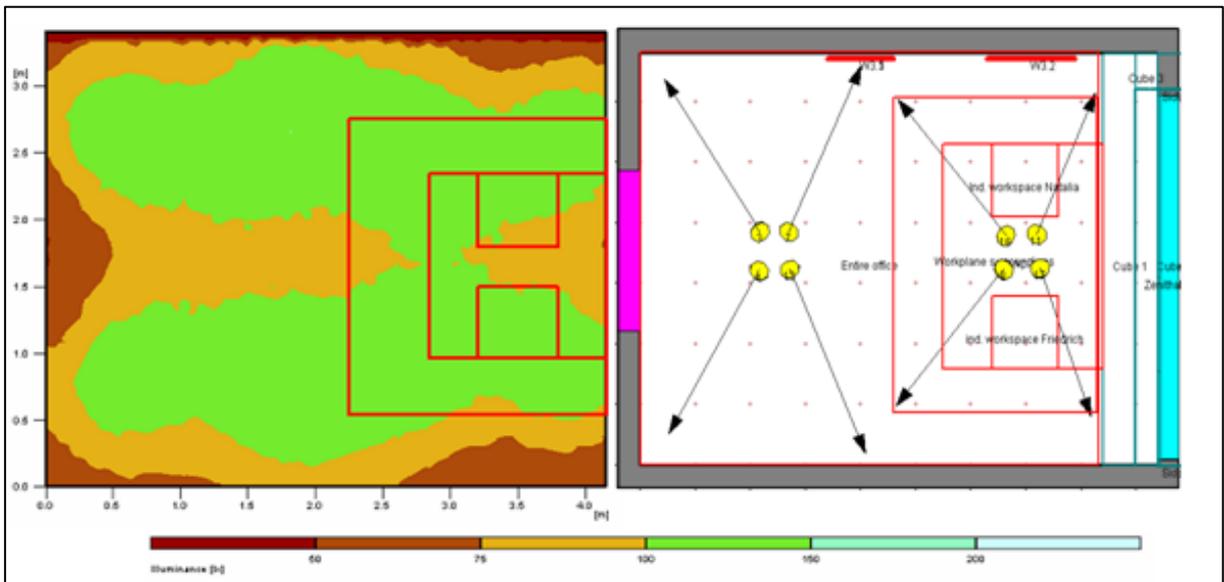

Figure 5.9: Third alternative lighting design including 8 luminaires. The LPD in this case is 3 W/m^2. This scenario is referred to as "Case 4".

Figure 5.10 illustrates the average illuminances for the five reference planes for each of the four cases as well as for the current best-practice installation. It can be observed that the 4.5 W/m^2 LED-solution (Case 1) clearly outperforms the current conventional installation (with an equal LPD of equally 4.5 W/m^2). The average illuminances of the 3 W/m^2 LED-design (Case 4) are substantially lower than those of the current installation. The design showing an LPD of 3.75 W/m^2 (Case 2) performs worse than the current installation in terms of average illuminances; "Case 3" yields average illuminances comparable to those of the current installation. It is interesting to note that that the latter offers a 10.4 % average illuminance enhancement than "Case 2". This improvement has been achieved only through a different

luminaire positioning. It underlines the significance of a proper planning when designing energy-efficient lighting solutions.
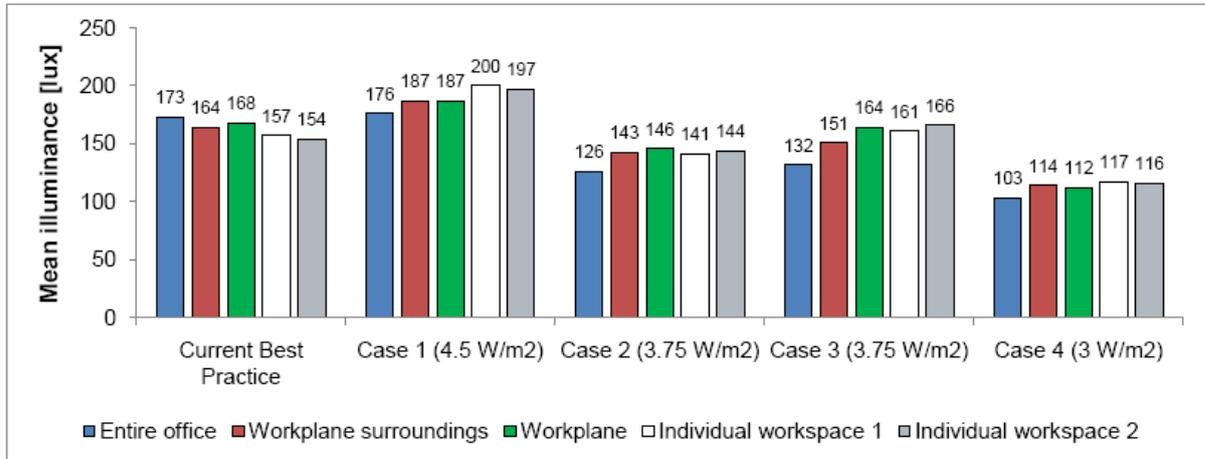
Figure 5.10: Average illuminances for the five reference planes for each of the four cases as well as for the current best-practice installation.

The corresponding illuminance uniformities for the different reference planes are shown in Figure 5.11. Cases 1 through 4 yield uniformities comparable to those of the current lighting installation. All cases can therefore be expected to provide an appropriate visual comfort in terms of lighting uniformities.
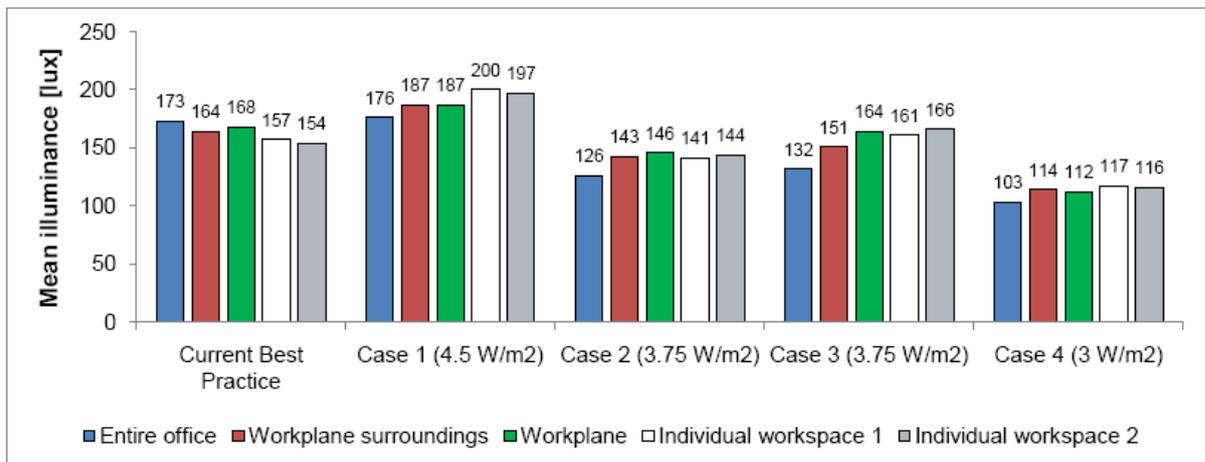
Figure 5.11: Average illuminance uniformities for the five reference planes for each of the four cases as well as for the current best-practice installation.

Figure 5.12 illustrates the simulation of a 3.25 W/m^2 LED-lighting design eight Altea LED Bianco luminaires were used and two additional high power LED sources (OSRAM) were placed right above the individual workspaces. The resulting illuminance distribution at a reference height of 80 cm above floor level is shown in Figure 5.12 (left) whereas Figure 5.12 (right) shows the positioning of the LED luminaires on the office room's ceiling.
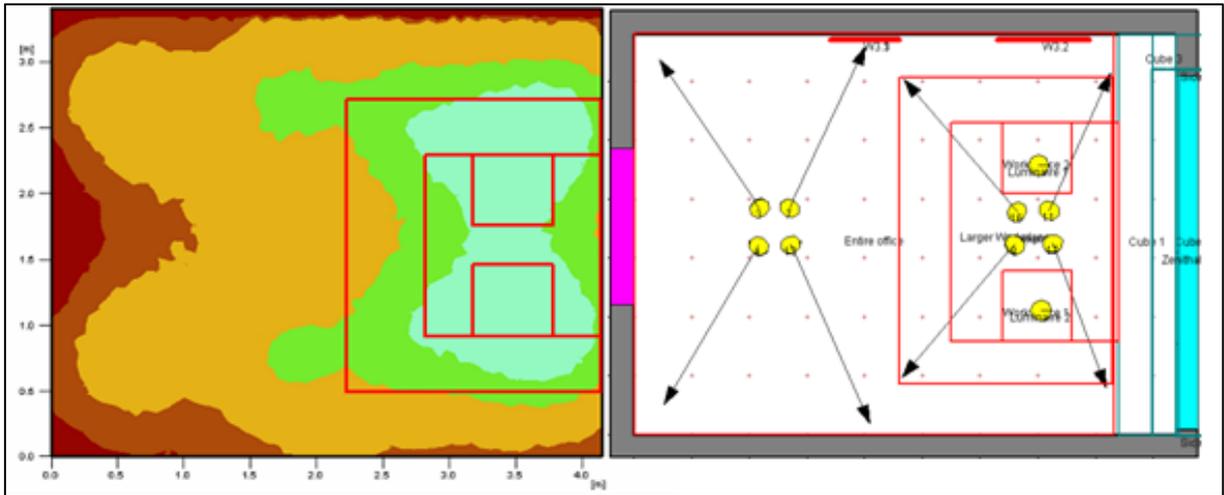
Figure 5.12: Simulation of a 3.25 W/m² LED-lighting design where eight Altea LED Bianco luminaires was used and two additional high power LED sources (OSRAM) were placed right above the individual workspaces.

Figure 5.13 shows the resulting average illuminances and uniformities g_1 for the lighting design illustrated in Figure 5.12. The obtained illuminance values are comparable to those presented by Linhart and Scartezzini in 2009 [Linhart and Scartezzini, 2009], the uniformities being reasonably good. The lower values for the reference plane "entire office" are due to very low illuminances near the door, what might not be too annoying to office workers. In any case, this simulated lighting design is a promising configuration to be tested in a future POE study in the LESO solar experimental building.
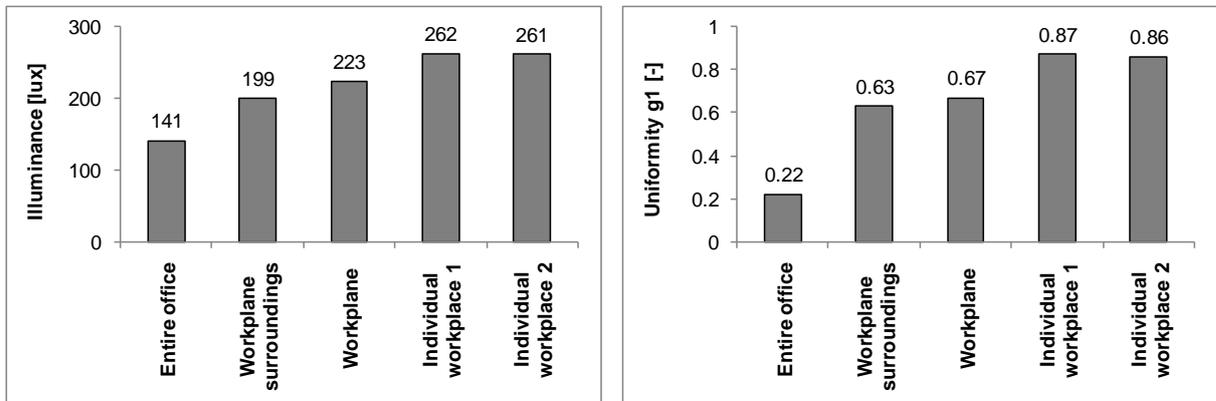
Figure 5.13: Resulting average illuminances and uniformities g1 for the lighting design illustrated in Figure 5.12.

These simulations involving white LED light sources have been carried out in 2007 and 2008. At that time, very few LED luminaires for general lighting were available and almost none of them were implemented in the RELUX software tool. As previously explained, a modified version of the Altea LED Bianco 180 mm LED luminaire (generally employed for decorative lighting) was used for that reason. There are still few LED luminaires available today for RELUX simulations, but the situation is evolving rapidly. Especially lamp and luminaire manufacturers from China keep on putting new LED products on the market. Figure 5.14 shows different LED lighting products currently available on the market.

Figure 5.14: Various LED light sources. a): 1 W white LED lamp with GU10 socket (Paulmann), b): 2.5 W white LED lamp with E27 socket (Paulmann), c): 7 W white LED bulb with E27 socket (PHILIPS), d) 1 W white LED task lighting application (IKEA), e) Swan neck white LED with USB socket, f) Battery-driven white LED task lighting application (OSRAM), g) 3.4 W white power-LED application (OSRAM).

In addition to the LED products illustrated above, white "LED tubes", which can be mounted in luminaires for retrofit instead of regular fluorescent tubes have recently become available on the market. Such an "LED tube is shown in Figure 5.15.

Figure 5.15: White LED tube for retrofit in luminaires instead of fluorescent tubes.

Within the framework of the Green Lighting project, we have just recently started in-depth tests with two such LED-tubes (one warm white and one pure white tube) with a power consumption of 22 Watts and an announced output flux of 1950 lumens. This corresponds to a luminous efficacy of 89 lm/W. Figure 5.16 shows the "pure white" tube in operation in an experimental setup.

5.16: White LED tube for general lighting in operation.

Replacing fluorescent tubes with such LED tubes is, however not in all cases straightforward. In luminaires with conventional control gear (i.e. inductive ballasts) all one has to do is to remove the starter from the luminaire. Then, the fluorescent tube can be replaced with the

LED tube. Replacing fluorescent tubes in modern luminaires with electronic control gear is unfortunately more complicated. In such luminaires, the wiring will have to be modified by an electrician before retrofitting the luminaire with an LED tube. This is likely to create practical problems in many cases. However, the described LED tubes might become an interesting option for office lighting solutions in the very new future, especially as luminous efficacies of white LEDs are further improving.

We are planning to run more experiments in one of our test offices within the LESO building with such LED tubes as soon as possible.

5.3   LED for task lighting

Within the framework of the Green Lighting project, two LED light bulbs were tested in a task lighting application: the PHILIPS Master LED Bulb "Cold white" (showing a luminous efficacy of 32.9 lm/W) and the PHILIPS Master LED Bulb "Warm White" (showing a luminous efficacy of 22.1 lm/W). [www.philips.com, 2009] The latter is shown in Figure 5.17.
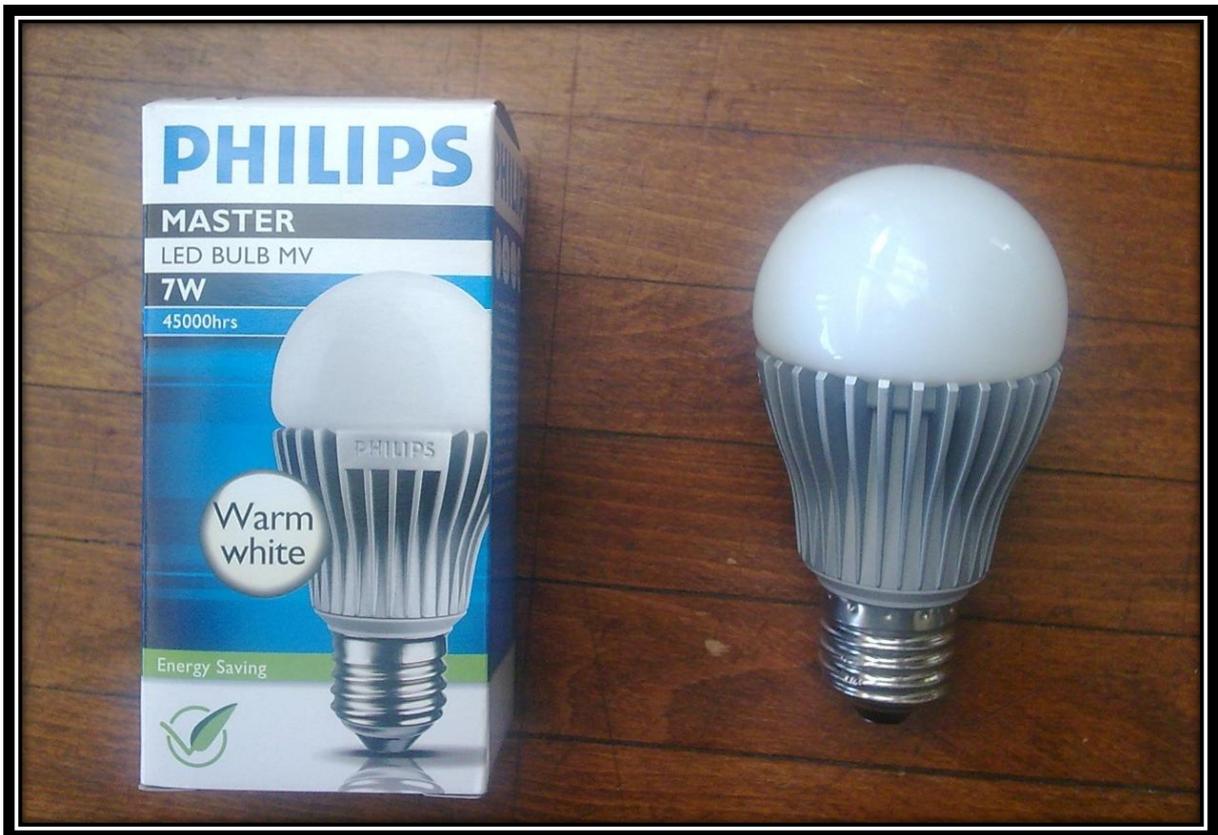
Figure 5.17: PHILIPS Master LED Bulb "Warm White" (showing a luminous efficacy of 22.1 lm/W).

For both lamps, a lifetime of 45'000 hours is announced by the manufacturer. A comparable CFL produced by the same manufacturer (PHILIPS Genie WW 827) comes with a luminous efficacy of 54.5 lm/W and a lifetime of 8000 hours. If we assume a market price of approximately 100 CHF for the LED light bulbs and a market price of approximately 10 CHF for the CFL lamps (corresponding offers can be found on the internet), this yields an installation costs of 2.22 CHF/1000 operating hours for the LED bulbs and 1.25 CHF/1000 operating hours for the CFL. In terms of luminous efficacy and cost, white LED bulbs are therefore not yet competitive compared to CFLs. They have, however, one important advantage in terms of ergonomic handling compared to the latter.

This advantage is illustrated in Figure 5.18. It shows the monitored relative workplane illuminance obtained with the desk lamp shown in Figure 3.11 for the cases where the latter is either equipped with one of the PHILIPS LED bulbs, with the PHILIPS Genie CFL or with a low-budget CFL from IKEA.
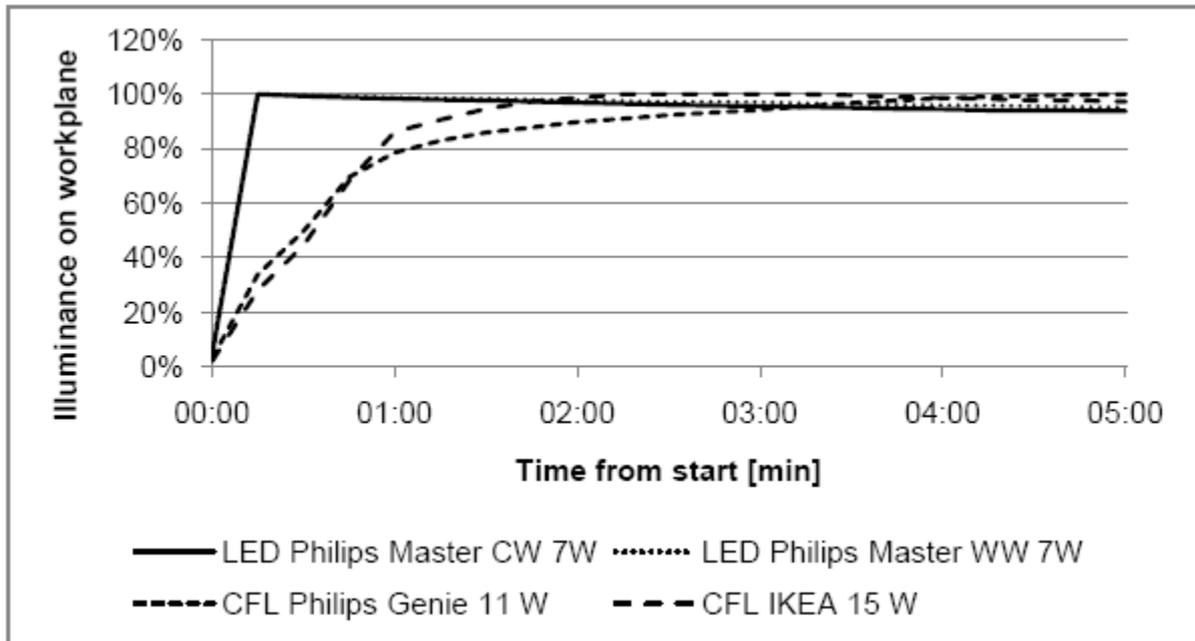
Figure 5.18: Monitored relative workplane illuminance obtained with the desk lamp shown in Figure 3.11 for the cases where the latter is either equipped with one of the PHILIPS LED bulbs, with the PHILIPS Genie CFL or with a low-budget CFL from IKEA.

It is evident that both CFLs need significantly more time for reaching their maximum light output than the two LED bulbs due to the necessary warming up of the plasma in the CFL tube. The LEDs immediately reach their maximum light flux, the 10 sec time delay being due to the sampling rate chosen for this experiment.

Figure 5.19 gives the time delay required by the four different lamps to reach at least 95% of their maximum light flux. It is interesting to note that the CFL from IKEA reached this threshold much quicker than the PHILIPS Genie CFL. It is also interesting to note that the workplane illuminance decreased slightly with time for the Philips Master LEDs (see Figure 5.18), a decrease of more than 5% over the first 5 minutes having been observed. This effect can be explained by the heating up of the LED and an associated deterioration of its semiconducting properties.
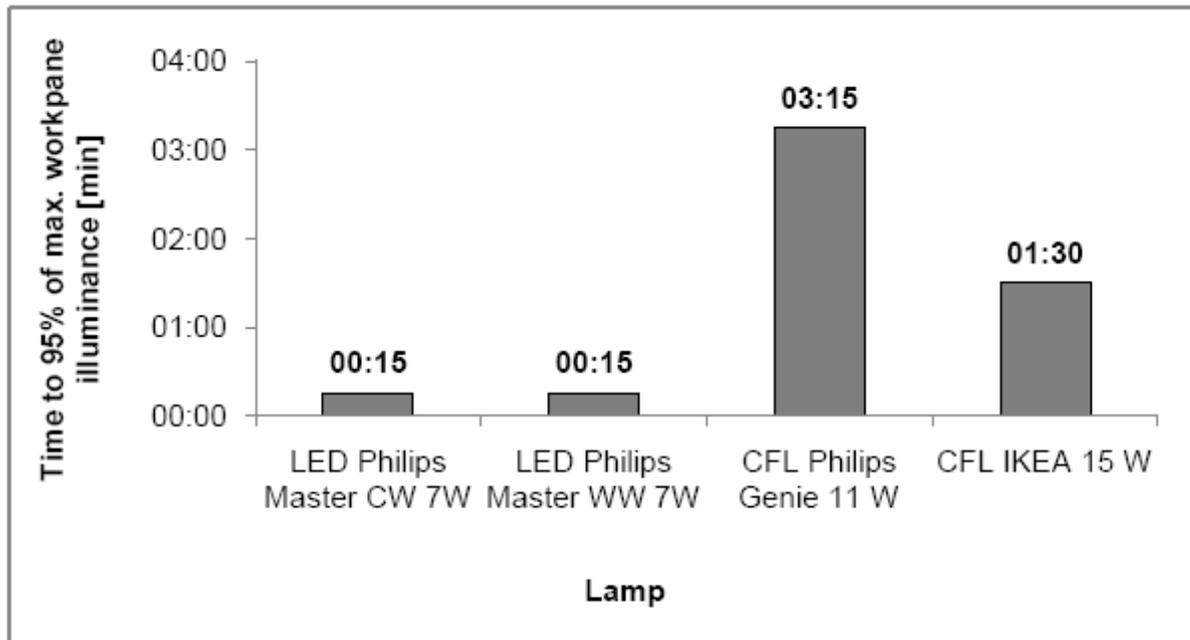
Figure 5.19: Time delay required by the four different lamps to reach at least 95% of their maximum light flux.

5.4   Future potential of Organic Light Emitting Diodes

The LED technology described in Sections 5.1 to 5.3 is making use of inorganic semiconductor materials for light generation. However, it is also possible to use organic materials: devices based on this technology are referred to as Organic Light Emitting Diodes (OLED).

OLEDs have several advantages compared to inorganic LEDs. Coupling out the light from the semiconductor material is for example easier than in inorganic semiconductor materials because there are less reflection losses at internal boundary layers. This is due to the fact that organic semiconductors tend to have lower permittivities than inorganic semiconductors. Another advantage is the fact that it is easy to manufacture OLEDs in different geometrical shapes, which gives a large variety of different design options. There are, however, also a few disadvantages of OLEDs compared to LEDs. Lower thermal stability, corrosion problems due to the penetration of oxygen and water into the material as well as the management of extremely complex manufacturing processes are issues that have to be dealt with.

There are two main application fields for OLED: displays and general lighting. Using OLED displays instead of LCD displays has several advantages, such as lower electricity consumption and lower installation depths. These advantages make them particularly interesting for portable devices. Apple's iPhone for example uses an OLED display. OLED displays are also often referred to as possible alternatives to "plasma" television screens. Companies like Samsung, Sony and Toshiba already have products on the market, but there are still significant problems to overcome. One of those problems is the fact that the different color pixels in OLED displays have different lifetimes. It is therefore difficult to guarantee appropriate color stability. The development of OLED devices for lighting applications is still at the very beginning and appropriate products are far from being widely available. Philips Lighting has started to promote their Lumiblade-line; the so-called "Lumiblade Experience Kits" (composed of small OLED panels and the corresponding electronic control gear) can be ordered via the Philips Lighting website. Such a demo-kit has been ordered for testing during the Green Lighting project. Figure 5.20 shows a white "Pixel"-Lumiblade in operation at our laboratory.
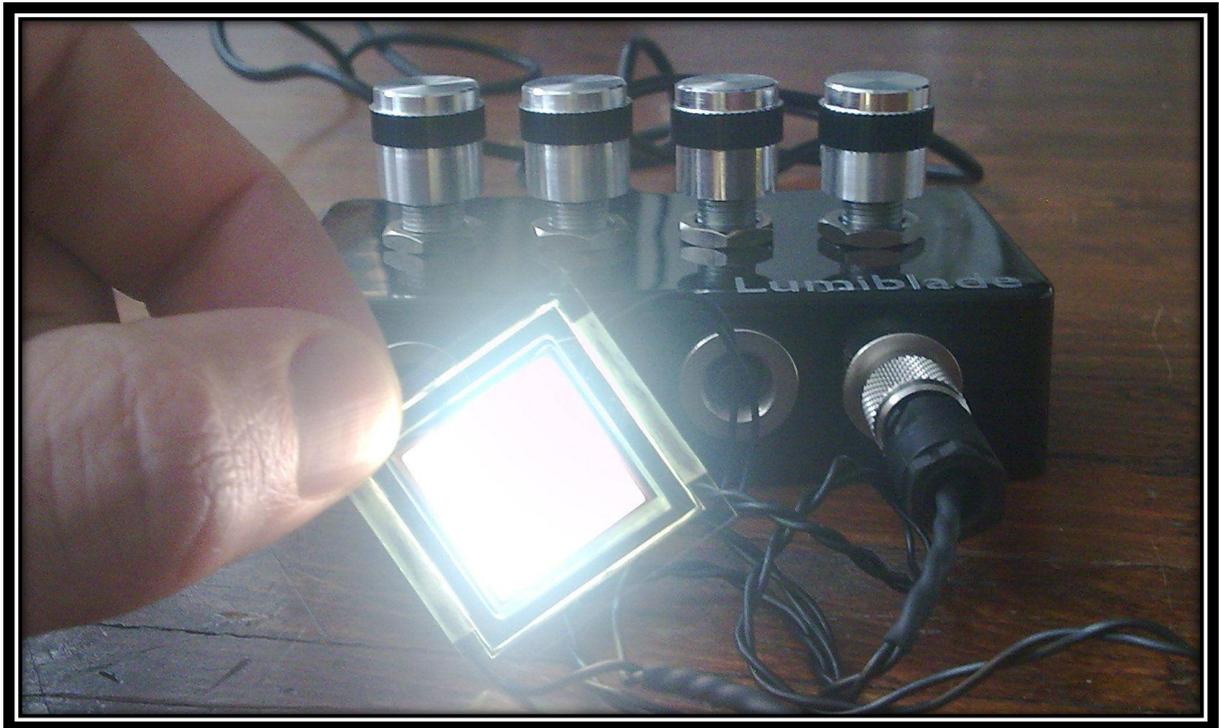
5.20: White Lumiblade OLED "Pixel" in operation at the LESO-PB.

It is clearly not designed for illumination but rather for demonstration purposes. Lifetime estimations are not yet available and we have already experienced unwanted "flickering" of the "Pixel"-Lumiblade after only very few minutes of operation.

The great advantage of the OLED for general lighting applications is the fact that (in principle) lambertian emitters of very large surfaces can be created. Additional optical devices for coupling out and distributing the light, such as luminaires, are not necessarily needed. In addition to that, it is possible to build OLED modules which are highly transparent when no current is applied to them. This possibility can be expected to offer interesting options for lighting design, such as the use of OLED layers on windows or daylighting systems. For the time being, speculating about the widespread use of such applications is nevertheless dreaming about the future. Envisaging the use of ceiling or wall-integrated OLED panels is however somewhat more realistic and such panels can be expected to become available for office lighting applications within the next two years.

5.5 Conclusion

The simulation and experimental results presented in this Section suggest that lighting applications based on white LEDs have real potential for becoming an alternative to low wattage fluorescent lighting within the next few years. This will probably also be the case for larger power light sources such as those used for indoor and outdoor illuminations.

OLEDs can also be expected to play a role in office lighting in the future, but it will probably still take several years before appropriate applications become available.

6 Application in different contexts

6.1 Anidolic Integrated Ceiling (AIC)

Besides the Advanced Daylighting System presented within the previous Sections, other types of ADS have also been developed over the last few years. The Anidolic Integrated Ceiling (AIC), first presented by Courret in 1999 [Courret and Scartezzini, 1999], is one of them.

Figure 6.1 shows an overview of an AIC mounted on a test module located on the campus of the Swiss Federal Institute of Technology in Lausanne/Switzerland (EPFL). The zenithal "Collector", covered by a double glazing, captures daylight from the sun and the sky vault. The two anidolic elements of the Collector redirect the daylight flux into the highly reflective "Duct" by which it is conducted to the "Distributor" element. The latter then distributes the light flux into the office room. Courret et al. have calculated an overall system efficiency of 32% (ratio of emerging light flux at the exit of the distributor and incoming light flux at the entry of the collector) [Courret et al., 1998].
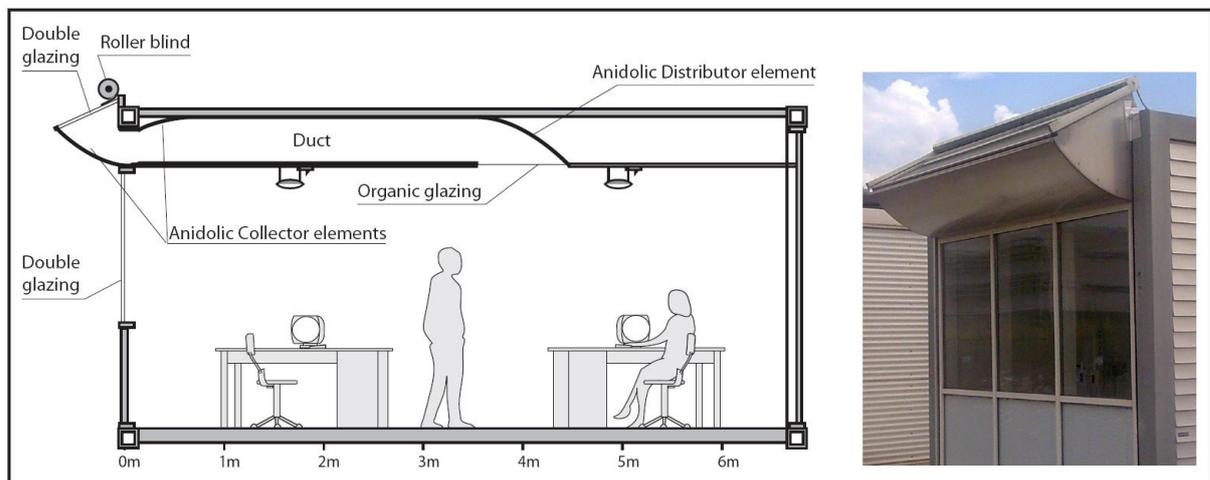
6.1 : Schematic overview of the AIC and test module located on the EPFL campus in Lausanne/Switzerland equipped with a prototype.

Using the AIC, rather than the ADS installed at the LESO solar experimental building, opens up interesting lighting options for larger office spaces where the daylight flux has to be transported to areas situated deeper towards the building core. This Section presents two studies concerning an AIC that have been carried out within the framework of the Green Lighting project. The first one explains how a highly energy-efficient integrated lighting system has been developed for an open plane office in Singapore, the second one discusses the use of highly reflective coating materials within an AIC.

6.2 Lighting Strategy for an Open Plan Office in Singapore

6.2.1 Introduction

Wittkopf et al. at the National University of Singapore (NUS) have recently shown that the AIC shown above can be expected to perform very well in tropical conditions [Wittkopf et al., 2006; Wittkopf, 2006]. According to their simulations, the fraction of the usual Singapore working day (08.00 until 18.00), during which the electric lighting system must be switched on due to insufficient daylight provision, is 75% for a reference office room in Singapore. The

simulations also show that in the same office room equipped with an AIC, this fraction can be reduced down to 54%. Under the assumption that the electric lighting system is automatically switched off when enough daylight is available to supply the required workplane illuminances, this corresponds to electric energy savings of 21% compared to the reference office room.

These interesting findings are an ideal starting point for applying some of the Green Lighting concepts to office rooms in tropical climates. In order to benefit from the increased light flux within the office room created by the AIC and to achieve maximum energy savings, the electric lighting system must be down-sized as much as possible. Because for the time being there is no knowledge on user satisfaction related to this type of ADS in Singapore (unlike the situation within the LESO solar experimental building in Switzerland), it makes sense to define a target lighting power density for Singapore that is slightly more conservative than the 3 W/m^2 adopted for Switzerland: a lighting power density of 5 W/m^2 is suggested as starting point. Once this system is installed in combination with the AIC, occupant satisfaction assessments, further simulations and in-situ measurements could be carried out in order to yield a proof-of-concept for this type of office room in Singapore.

6.2.2   Daylight performance of simulated office room

Wittkopf et al. considered a 6m x 6m Singapore office room with an AIC located 2.65m above floor level for their simulations. They have only taken into account diffuse skylight because this is typical for Singapore; obstructing surrounding buildings and their reflectance were also taken into account [Wittkopf et al., 2006]. The considered room is sidelit by a window (dimensions 5m x 1.85m) that is situated directly underneath the AIC, in the centre of one of the four walls. The reflection / transmission properties for the different room components are summarized in Table 6.1.

Table 6.1 : Reflection / transmission properties for the different room components as used by Wittkopf et al.

Surface	Reflectance / Transmittance [%]	Photometric property
Floor	20	ideal diffuse
Walls	50	ideal diffuse
Ceiling	80	ideal diffuse
Glazing	80	clear glass

A corresponding computer model of this Singapore office room was built up using RELUX Vision at the LESO-PB in 2007. Under the assumption that eight persons will occupy this office room, an appropriate energy-efficient electric lighting system has been designed. Fig. 6.2 shows a 3D-view of the corresponding model (so far there is no electric lighting system in place).
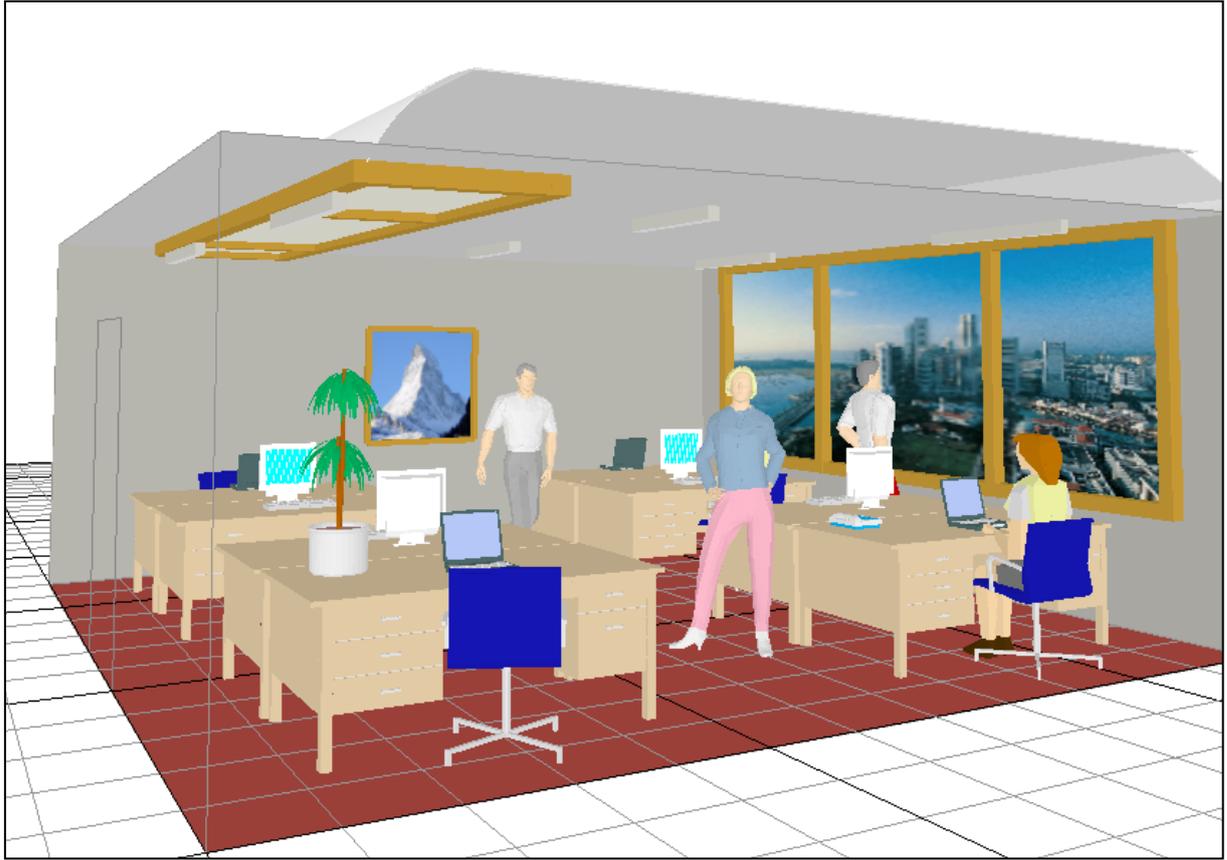
Figure 6.2 : 3D-view of the RELUX Vision computer model of the simulated Singapore office room.

Wittkopf et al. divided the 36 m^2 office room into three equal sections of 2m x 6m. The first one is situated near the window, the second one in the centre of the room and the third one in the rear. The average daylight autonomy, defined as the percentage of time over a user set period of time during which the illuminance due to daylight flux at a certain point is high enough to make additional artificial light dispensable, was then calculated for each section under the assumption that the conditions are identical for every day of the year [Wittkopf et al., 2006]. For this particular situation, these authors considered a 300 Lux daylight illuminance threshold above which electric lighting is dispensable. Table 6.2 summarizes the corresponding simulation results; Figure 6.3 visualizes the three equal sections and the resulting daylight autonomies from window section to rear section of the office room (DAW, DAC and DAR), the latter being equipped with side window and AIC.

Table 6.2 : Daylight autonomies for the three different room sections as given by Wittkopf et al.

Room section	DA [%] (only window)	DA [%] (window + AIC)
Window	74	63
Centre	1	11
Rear	0	64
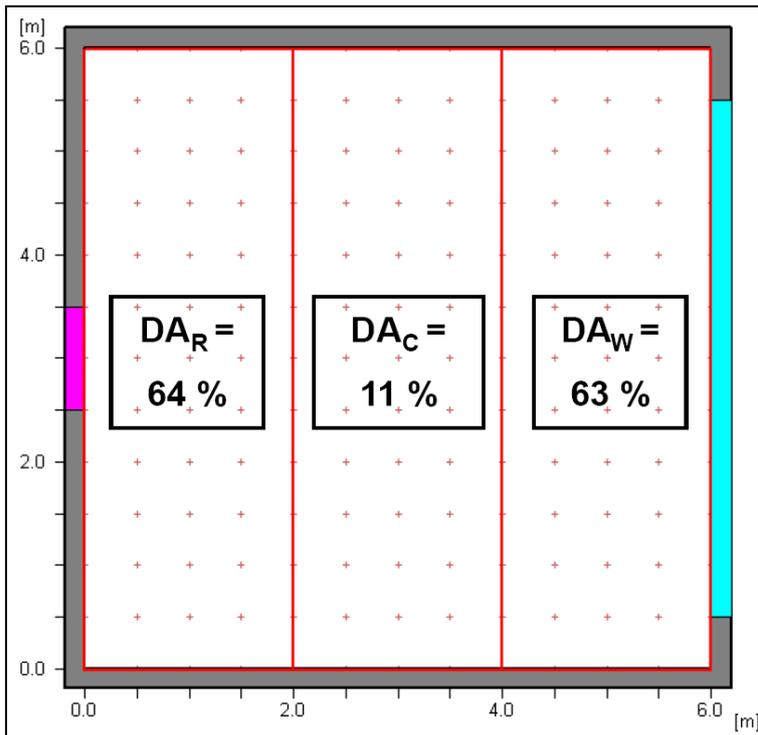
Figure 6.3: Office room subdivision into window, centre and rear section with the corresponding daylight autonomies (DA$_w$, DA$_c$ and DA$_r$) in the case of a window and an AIC.

Wittkopf et al. have predicted not only daylight autonomies for this type of office room in Singapore. In fact, it has also been shown that illuminance ratios (comparable to daylight factors, but defined for all sky types) for this office room can be expected to be comparably elevated [Wittkopf, 2006]. For the office's rear section for example, the author predicts an average illuminance ratio improvement factor of 2.2 compared to the same room without AIC. This improvement leads to illuminance ratios (or daylight factors) in the range of 6 to 7% in the rear section of the office room.

- These results clearly illustrate the excellent performance of AIC within this north-facing Singapore office. The installation of an AIC in this room has two advantages:

- The first one is that the room's window section is shaded because the AIC's external element is partly blocking the direct sunlight reaching the room; this leads to a reduced DA in this section (63% instead of 74%), but also to a reduced glare risk here.

The second advantage (yet more evident) is the significant increase of the DAs in the centre and the rear sections of the room.

This means that the AIC of the described office room in Singapore will provide sufficient daylight fluxes within the window and the rear section of the room during more than 60% of a usual Singapore working day. During the rest of the day, an auxiliary electric lighting system must be switched on to produce an additional artificial light flux in order to guarantee the required minimum illuminances. As for the centre section of the room, auxiliary artificial light flux will be necessary during 90% of a usual Singapore working day.

The office room thus requires an electric lighting system, which is able to supply an additional artificial light flux to the sections when there is not sufficient daylight available. In addition to that, the system has to be able to supply enough light for sporadic cases when persons wish to continue working later in the evening (or before sunrise).

6.2.3   Design and performance of an adequate electric lighting system

An adequate electric lighting system can be implemented using two "Tulux Zen 3"-luminaires equipped with a single 21 W high efficiency fluorescent tube each (luminaire connected power, including electronic control gear: 25 W) and four "Tulux Zen 3"-luminaires equipped with a single 28 W high efficiency fluorescent tube each (luminaire connected power, including electronic control gear: 32 W). A detailed luminaire description was given in Chapter 4 of this report. This installation leads to a lighting power density slightly lower than 5 W/m^2.
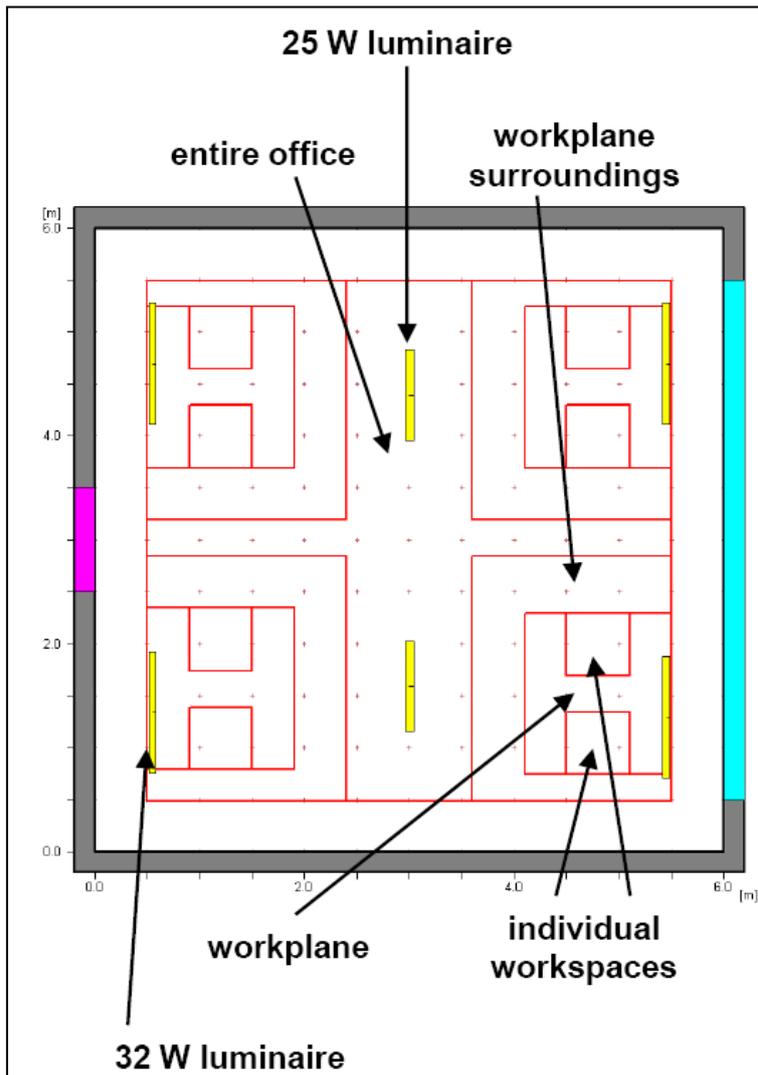
Figure 6.4: Integration of the six luminaires within the RELUX Vision model of the Singapore office room.

Figure 6.4 illustrates the integration of the six luminaires within the RELUX Vision computer model of the Singapore office room. The figure also shows 17 different reference planes, placed 0.75 m above floor level, which were chosen in order to assess the electric lighting system's performance; one main reference plane represents the entire office. A distance of 0.5 m was maintained between the walls of the room and this major reference plane. Four additional reference planes, called "workplane" in our model, were considered. These "workplanes" are placed directly on top of the eight office desks shown in Figure 6.2, each "workplane" covering simultaneously two desks. As it can be observed in Figure 6.4, a slightly larger reference plane, called "workplane surroundings", is placed around each workplane.

In addition to that, every workplane comprises two 0.6 m x 0.6 m "individual workspaces", which coincide with the desks shown in Figure 6.2. These are the regions where special visual tasks (for example reading or writing) are normally carried out. The "individual workspaces" require higher illuminances and uniformities than the rest of the room.

Table 6.3 gives an overview of the different reference plane types used in the computer model, as well as the corresponding required minimum average illuminances and uniformities.

Table 6.3 : Overview of the different reference plane types used in our model with corresponding minimum average illuminances and uniformities.

Reference plane	E_{Av} [lux]	Uniformity g1 [-]
Individual workspaces	300-500	0.7
Workplanes	300	0.7
Workplane surroundings	200-300	0.6
Entire office	200	0.6

Figure 6.5 (left) shows the simulation results in absence of daylight (only artificial light). One can observe the symmetric light distribution, as well as the fact that the illuminance maxima mostly coincide with the different workplanes and workspaces. All six luminaires are switched on.
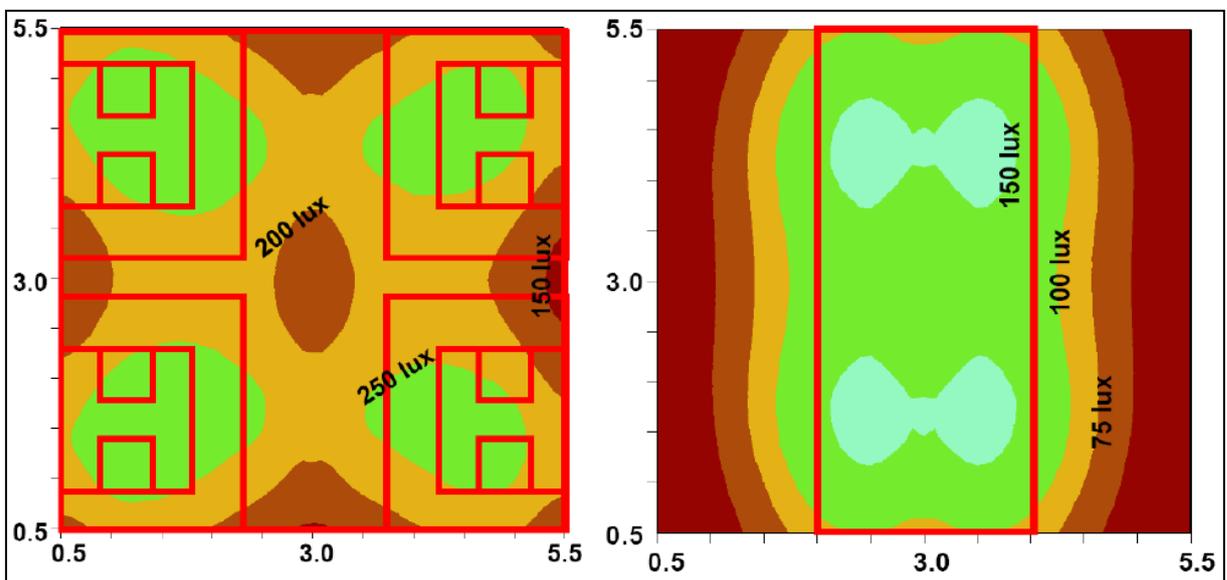
Figure 6.5 : Simulation results in absence of daylight when all three sections are switched on (left), and when only the centre section is switched on (right).

Figure 6.5 (right) shows the situation where only the two luminaires situated in the centre of the room are switched on. It can be observed that they mainly illuminate the centre of the room and still achieve a good uniformity. The resulting illuminances in the rear and window section of the room rapidly drop when leaving the centre section. This situation will occur only when the daylight flux reaching the centre section is not sufficient but the daylight flux reaching the rear and window section is appropriate.

Table 6.4 shows the average illuminances E_{av} and the uniformities g1 for the different reference planes illustrated in Figure 6.4. The values for the workplane surroundings, the workplanes and the individual workspaces correspond to the average obtained for each type of reference plane. Standard deviations are 7.9, 10.1 and 11.3 [Lux] for the illuminances and 0.03, 0.02 and 0.03 [-] for the uniformities.

Table 6.4 : Average illuminances E_{av} and the uniformities g1 for the different reference planes illustrated in Figure 6.5 (left).

Reference plane	E_{Av} [lux]	Uniformity g1 [-]
Individual workspaces	259 +/- 4.4%	0.85 +/- 3.0%
Workplanes	252 +/- 4.0%	0.7 +/- 3.3%
Workplane surroundings	234 +/- 3.4%	0.64 +/- 4.1%
Entire office	230	0.6

When comparing these results with the target values given in Table 6.3, one can observe that the uniformity requirements are fully satisfied. In particular, the uniformities on the individual workspaces are extremely elevated. The average illuminances show appropriate values on the reference planes "entire office" and "workplane surroundings" only. However, it has to be kept in mind that the electric lighting system in this office room is intended to be complementary to daylight during usual Singapore office hours. This means that when the daylight flux that reaches the window and rear section of the room is large enough to create 50 Lux average illuminances on the workplanes and individual workspaces, the electric lighting system will be capable to raise the overall illuminances above the required values (specified in Table 6.3 on all reference planes). In addition to that, it can be assumed that even people occasionally working at night will be satisfied with this system: occupants of anidolic offices in Switzerland, who sometimes work at nighttime, accepted workplane illuminances that are significantly lower than the recommendations listed in Table 6.3 [Linhart and Scartezzini, 2006].

The situation shown in Figure 6.5 (right) (only the two luminaires located in the room's centre section switched on) leads to an average illuminance of 132 Lux and a uniformity of 0.68. If we keep yet again in mind that this situation only occurs when there is enough daylight flux to provide the required illuminance levels in the rear and window sections of the room, we can consider the complementary electric lighting system to be appropriate during this situation as well.

If we consider that at every moment when the daylight flux in one of the room's sections is not sufficient (i.e. lower than 300 Lux) complementary electric lighting is automatically switched on in the corresponding section, then the average daily electricity demand for electric lighting within an office room during a usual Singapore working day can be found by applying the following equation:

$$E_{lighting} = \sum_{x=R,C,W} ((100\% - DA_x) * P_{lighting,x}) * 10h \qquad \text{(Equation 7)}$$

In this equation, DA_x stands for a section's daylight autonomy whereas $P_{lighting,x}$ represents the installed lighting power within this section. With $P_{lighting,R} = P_{lighting,W} = 64W$ and $P_{lighting,C} = 50W$ we find a daily electricity consumption of 0.912 kWh for the office. Additional dimming strategies can further reduce this maximum electricity consumption.

6.2.4   Aesthetic aspects of building integration and expectable cost

Façade-integrated daylighting systems not only have to create a comfortable lighting environment inside a building: an appealing external building design must also be achieved.

Anidolic facades are not only able to meet common aesthetic requirements of building design. In fact, they can even be used to emphasize a building's façade. According to Altherr and Gay [Altherr and Gay, 2002], the anidolic façade of the LESO solar experimental building in Lausanne (see Figure 2.1) is well balanced from an architectural point of view. Its zigzag movement allows a clear distinction between the windows themselves and the anidolic elements [Altherr and Gay, 2002]. Another good example for the successful application of façade-integrated daylighting systems is the refurbished building of "Vakantiefonds Bouw" in Brussels/Belgium, suggested by Samyn and Partners in 1996 [Cardani, 1998]. It can be expected that appealing façade designs incorporating the presented AIC can also be realized in Singapore.

Until this day, only prototypes of the AIC presented in this paper exist. It is therefore not yet possible to quantify the expectable cost of the considered installation in a reasonable manner. Nevertheless, it can be assumed that a commercial AIC-façade would be around 20% more expensive than an average façade in most cases, depending on material and installation costs. Costs for system maintenance are very low, the AIC being a passive system and bi-annual cleaning of the system being far and away sufficient. The components suggested for the artificial lighting design are commercially available luminaires and fluorescent tubes, pricewise comparable to lighting equipment installed in buildings with conventional facades. The proposed electric lighting system can even expected to cost less than a conventional installation (less material needed due to lower LPD).

6.2.5   Conclusion

The results obtained during this study make it clear that Green Lighting concepts can be applied to a variety of settings with LPDs still below 5 W/m^2. The system discussed here will lead to a daily electricity consumption lower than 1 kWh per working day; an aesthetic and cost-effective integration of the system in building design is possible. The suggested electric lighting system can be used as a starting point in a 1:1 scale test setup in Singapore. Occupant satisfaction assessments, further simulations and in-situ monitoring can contribute to optimize this energy-efficient lighting solution for open space of office room in Singapore.

6.3   Splitting up the Anidolic Integrated Ceiling into small pieces: Cost optimization of AIC reflective components

6.3.1   Introduction

Amongst other factors, the reflective coating material has a major impact on the efficiency of the AIC. The best-performing reflective coating materials currently available on the market reach total reflections [Deutsches Institut für Normung, 1979] of 98% (e.g. MiroSilver™ by ALANOD [ALANOD, 2009]). Using such highly reflective coating materials on the entire AIC of course yields the largest optical efficiency, but it is also the most expensive solution. The questions are therefore: Which parts of an AIC should be coated with which reflective material? How do we get good trade-offs between efficiency and cost?

A new computer model of the AIC has recently been developed during a joint project between EPFL and the National University of Singapore (NUS). The great advantage of this new model is the fact that it consists of more than 30 different components. Different coating materials can be assigned to each of them. This makes it possible to identify those AIC components, where the use of expensive, highly reflective coatings makes the most sense

and other components, where cheaper materials can be used without significantly decreasing the AIC's overall optical efficiency.

So far, all simulations carried out for this particular system [Wittkopf, 2006; Courret et al., 1998] were based on a basic computer model where the entire AIC was considered as one piece. A global specular total reflection of 90% has been assigned to the entire AIC in this case. Within the framework of the design of a Zero Energy Building in Singapore, we have optimized this basic computer model and have carried out various simulations for Singapore sky conditions using the software tool Photopia 3.0 [Lighting Technologies, 2009]. In this new model, the AIC is not represented as one single piece, but has rather been split up into different components. Theoretically, we can assign a different coating material to each single component. This opens a whole lot of new simulation options and is an important step towards the development of optimized ADS.

6.3.2 Methodology

Figure 6.6 shows the main elements into which the "Collector" part of the AIC can be split up. The elements "Collector Side" could additionally be split up into eight distinct sub-elements, the elements "Anidolic Collector 1" and "Anidolic Collector 2" into six distinct sub-elements.
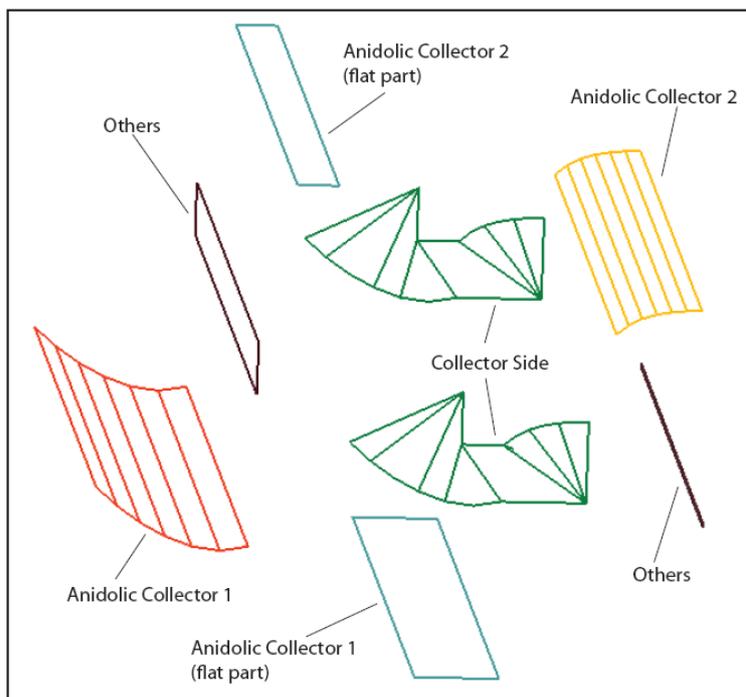
Figure 6.6 : Main elements of the AIC's "Collector" part.

The elements into which the "Duct" and the "Distributor" parts can be split up are shown in Figure 6.7. It is possible to additionally split the element "Anidolic Distributor" into six sub-elements and the "Distributor Sides" into three sub-elements each.
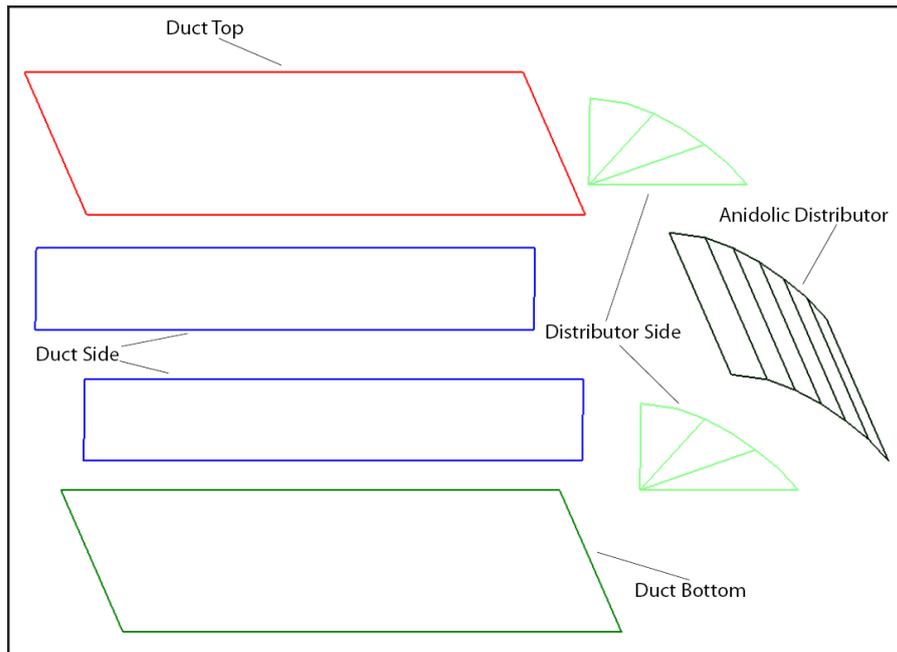
Figure 6.7 : Main elements of the AIC's "Duct"- and "Distributor"-parts.

Each of the AIC elements shown in Figures 6.6 and 6.7 was saved on a separate layer in an AutoCAD file. This file was then imported as a luminaire into the software Photopia.

During the computer simulations, a Virtual Sky Dome (VSD) [Wittkopf et al., 2006; Wittkopf, 2004; Wittkopf, 2005] was used as a light source. A VSD is basically a hemisphere composed of 145 subdivisions. It imitates the spatial luminance distribution of the sky vault by 145 distinct light sources whose distribution over the hemisphere follows the conventions of sky patch luminance IDMP monitoring protocol and whose individual luminous flux are calculated using a special set of equations for the 15 CIE sky types [Kittler et al., 2006; Kittler and Darula, 2002]. The appropriate luminances for each VSD patch have been calculated following the definition of the Singapore Representative Sky, previously used by Wittkopf et al. [Wittkopf et al., 2006].

Figure 6.8 shows a graphical representation of the VSD and the sky patch luminances used during the simulations. This VSD was imported into Photopia as a light source. The AIC was fixed under the VSD in such a way that the centre of the AIC's entry coincided with the VSD-hemisphere's centre. Via Photopia's menu "Design Properties", the different elements' reflective coatings were then gradually switched from "specular 90%" (the reference coating) to MiroSilver™.

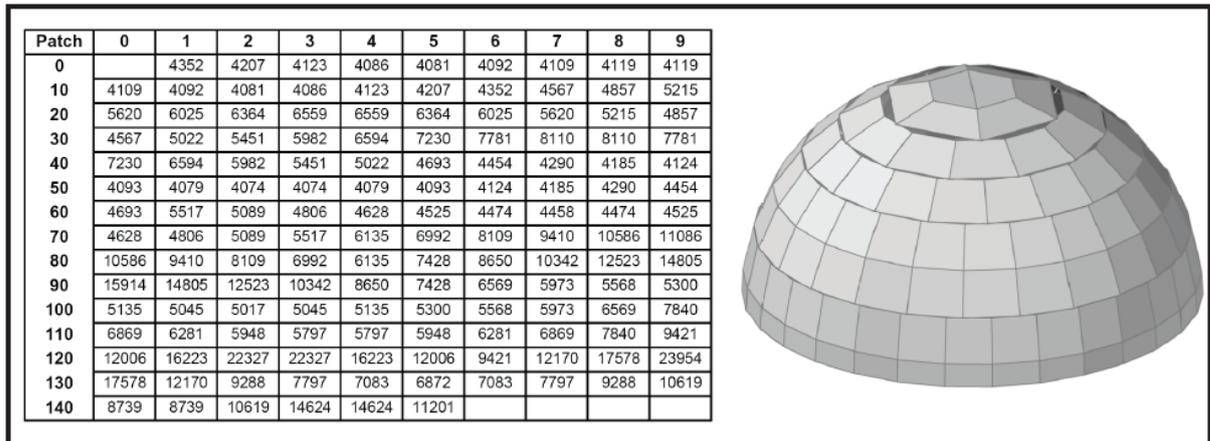| Patch	0	1	2	3	4	5	6	7	8	9
0		4352	4207	4123	4086	4081	4092	4109	4119	4119
10	4109	4092	4081	4086	4123	4207	4352	4567	4857	5215
20	5620	6025	6364	6559	6559	6364	6025	5620	5215	4857
30	4567	5022	5451	5982	6594	7230	7781	8110	8110	7781
40	7230	6594	5982	5451	5022	4693	4454	4290	4185	4124
50	4093	4079	4074	4074	4079	4093	4124	4185	4290	4454
60	4693	5517	5089	4806	4628	4525	4474	4458	4474	4525
70	4628	4806	5089	5517	6135	6992	8109	9410	10586	11086
80	10586	9410	8109	6992	6135	7428	8650	10342	12523	14805
90	15914	14805	12523	10342	8650	7428	6569	5973	5568	5300
100	5135	5045	5017	5045	5135	5300	5568	5973	6569	7840
110	6869	6281	5948	5797	5797	5948	6281	6869	7840	9421
120	12006	16223	22327	22327	16223	12006	9421	12170	17578	23954
130	17578	12170	9288	7797	7083	6872	7083	7797	9288	10619
140	8739	8739	10619	14624	14624	11201				

Figure 6.8 : Graphical representation of the VSD and the sky patch luminances used during our simulations.

6.3.3   Results

At the beginning of the study, we carried out five initial computer simulations: one reference simulation where the entire AIC was coated with a specular anodized aluminum coating (90% total reflection), one where the entire AIC was coated with the highly reflective MiroSilver™ coating (98% total reflection), and three where this coating was applied to the entire "Collector", the entire "Duct" and the entire "Distributor", respectively (the other components where kept at 90% total reflection in those latter cases). The overall optical efficiency of the reference AIC is equal to 32.5%. Figure 6.9 (left) gives an overview of the remaining four of the initial simulation runs. Coating the entire AIC with MiroSilver™ leads to an overall efficiency of 49%. This corresponds to a relative efficiency improvement of 50.8% compared to the reference case (efficiency of 32.5%). Coating either the "Collector", the "Duct" or the "Distributor" with MiroSilver™ resulted in relative efficiency improvements of 15.4%, 22.2% and 6.5%, respectively.
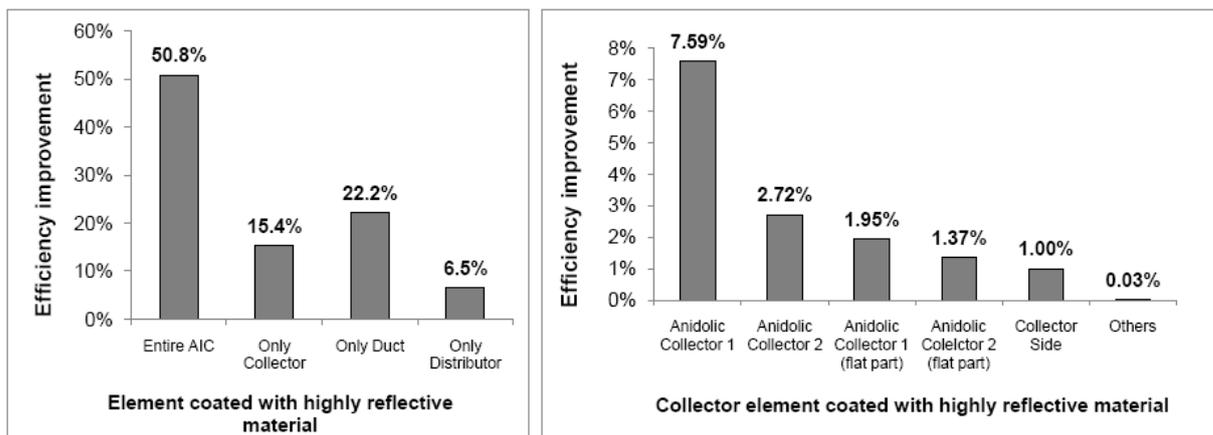
Figure 6.9 : Relative efficiency improvement (compared to the reference case where the entire AIC is coated with a 90%-total reflection anodized aluminum coating) when coating the entire AIC or either the Collector, the Duct or the Distributor with MiroSilver™ (left). Obtained relative efficiency improvements for the different Collector elements when only one of these elements is coated with MiroSilver™ (right).

During the following simulations, only one AIC element per simulation run (or one group of elements for the side elements and the "Others", see Figures 6.6 and 6.7) was coated with MiroSilver™; all other elements remained coated with the reference coating. Figure 6.9 (right) shows the obtained relative efficiency improvements for the different "Collector"

elements. They range from almost no improvement (in the case where only the "Other" elements are coated with MiroSilver™) up to an efficiency improvement of 7.59% in the case where the "Anidolic Collector 1" is coated with this highly reflective material.
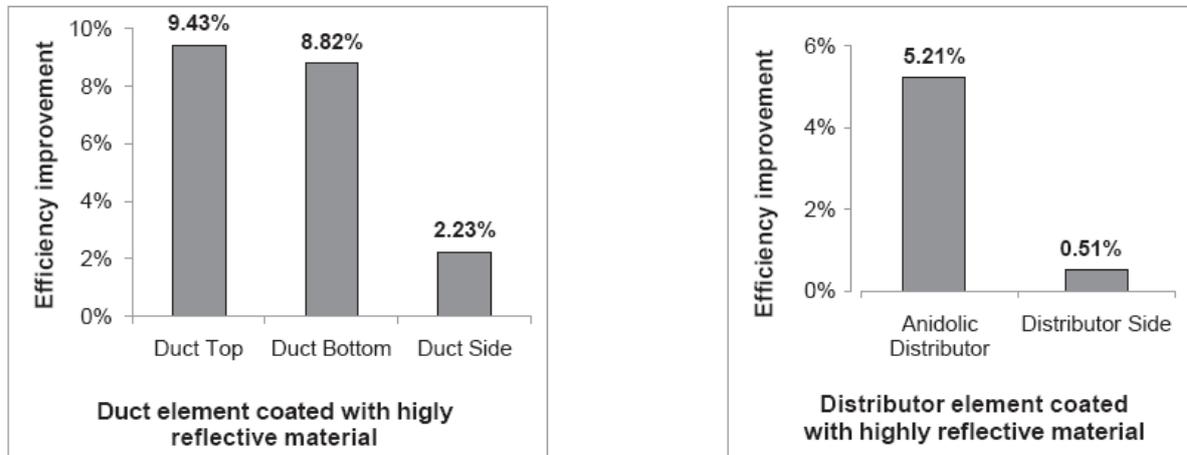

Figure 6.10 : Obtained relative efficiency improvements for the different Duct elements (left) and the different Distributor elements (right) when only one of these elements is coated with MiroSilver™.

Figure 6.10 (left) shows the efficiency improvements obtained during the three simulation runs where one "Duct" element at a time was coated with MiroSilver™. The corresponding efficiency improvements for the two "Distributor" elements are displayed in Figure 6.10 (right).

Based on the results of these initial simulations, we have then carried out an additional 11-step simulation series during which we have gradually coated all AIC elements with MiroSilver™. Table 6.5 shows the chosen steps for this simulation series. Taking the reference AIC as a starting point (Step 0), we have first coated the "Duct Top" with MiroSilver™ because this leads to the highest immediate efficiency improvement (see Figure 6.10 (left)). Subsequently, the same logic was used (i.e. always coating the element that can be expected to lead to the highest immediate efficiency improvement). As a matter of fact, in Step 2 the "Duct Bottom" was coated, in Step 3 the "Anidolic Collector 1" and so on. In this way, we obtained a maximum efficiency improvement while changing the coating on a minimum number of elements (Quickest Efficiency Improvement).

Table 6.5 : Simulation steps for the efficiency improvement strategy "Quickest Efficiency Improvement".

Coating Step	AIC elements coated with MiroSilver™
Step 0 (Reference)	none
Step 1	Duct Top
Step 2	All the above & Duct Bottom
Step 3	All the above & Anidolic Collector 1
Step 4	All the above & Anidolic Distributor
Step 5	All the above & Anidolic Collector 2
Step 6	All the above & Duct side
Step 7	All the above & Anidolic Collector 1 (flat part)
Step 8	All the above & Anidolic Collector 2 (flat part)
Step 9	All the above & Collector Side
Step 10	All the above & Distributor Side
Step 11	All AIC elements

Figure 6.11 shows the obtained relative efficiency improvement for each of the steps listed in Table 6.5. For comparative reasons, the theoretical curve obtained through simple addition of

the efficiency improvement values for the distinct components (see Figure 6.9 (right) and Figure 6.10) is also plotted in Figure 6.11.
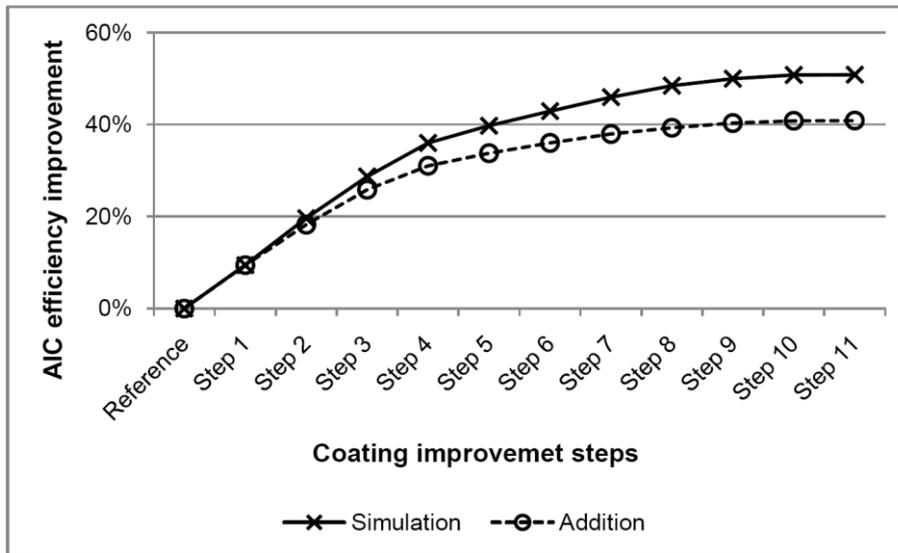

Figure 6.11 : Obtained efficiency improvement for each of the steps listed in Table 6.5.

The efficiency improvement sequence outlined in Table 6.5 was set up based on the absolute efficiency improvements for the distinct AIC elements shown in Figure 6.9 (right) and Figure 6.10. However, it also makes sense to look at the efficiency improvements per surface area (surface-specific efficiency improvement) of each distinct AIC component that is coated with MiroSilver™. Table 6.6 gives an overview of all AIC elements' surface areas.

Table 6.6 : Overview of all AIC elements' surface areas.

AIC element	Surface area [m^2]
Anidolic Collector 1	4.74
Anidolic Collector 2	2.49
Anidolic Collector 1 (flat part)	2.335
Anidolic Collector 2 (flat part)	1.15
Collector Side	0.492
Others	1.595
Duct Top	14.4785
Duct Bottom	14.4785
Duct Side	1.39008
Anidolic Distributor	5.41
Distributor Side	0.306

Figure 6.12 shows the surface-specific efficiency improvements based on the results of the "one at a time"-simulations (see Figure 6.9 (right) and Figure 6.10) and the surface areas of the different AIC elements given in Table 6.6.
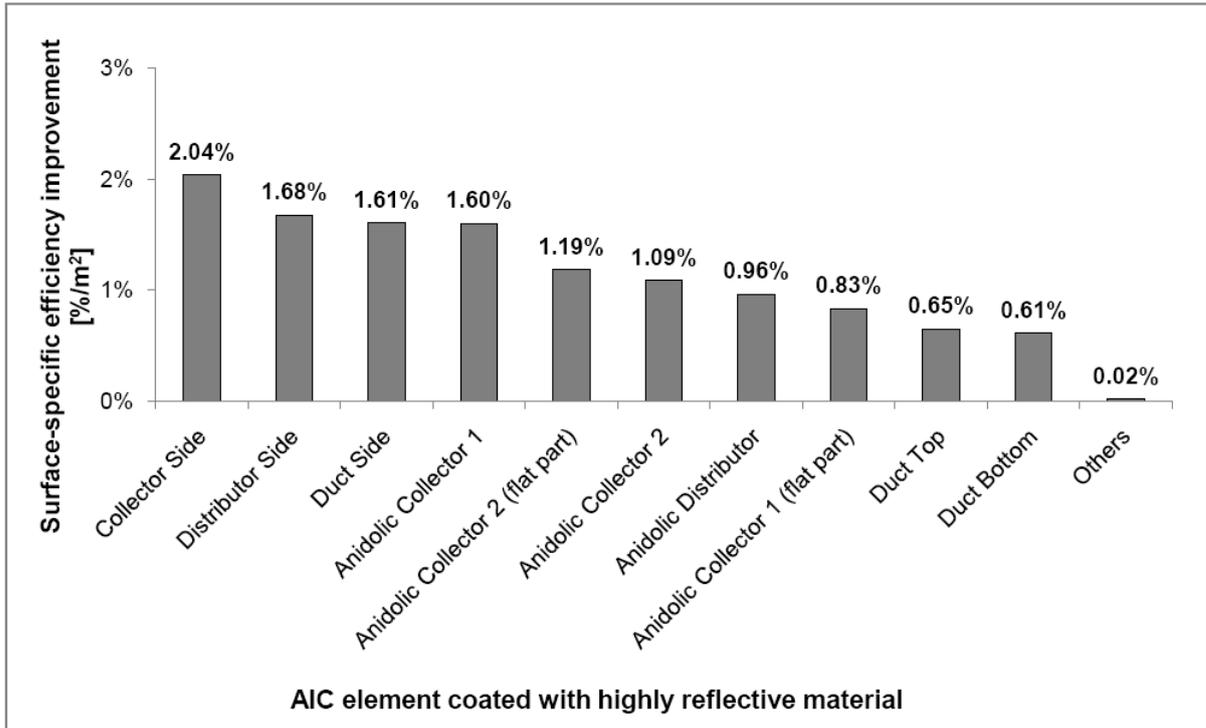
Figure 6.12 : Surface-specific efficiency improvements (expressed in per cent per square meter) for the different main AIC elements.

Based on these surface-specific efficiency improvements, a second efficiency improvement sequence was defined. In perfect analogy with the sequence described in Table 6.5, an 11-step simulation series was carried out, during which we have gradually coated all AIC elements with MiroSilver™. However, instead of always coating the element that leads to the highest immediate efficiency improvement, the steps of this second sequence were determined by the surface-specific efficiency improvements displayed in Figure 6.12. In this way, the best possible trade-off between efficiency improvement and amount of MiroSilver™ coating material was guaranteed in each improvement step (Minimal Coating Material). This second efficiency improvement sequence is outlined in Table 6.7. It starts off by coating the "Collector Side" (surface-specific efficiency improvement of 2.04% per m^2), then the "Distributor Side" (surface-specific efficiency improvement of 1.68% per m^2) and so on.

Table 6.7 : Simulation steps for the efficiency improvement strategy "Minimal Coating Material".

Coating Step	AIC elements coated with MiroSilver™
Step 0 (Reference)	none
Step 1	Collector Side
Step 2	All the above & Distributor Side
Step 3	All the above & Duct Side
Step 4	All the above & Anidolic Collector 1
Step 5	All the above & Anidolic Collector 2 (flat part)
Step 6	All the above & Anidolic Collector 2
Step 7	All the above & Anidolic Distributor
Step 8	All the above & Anidolic Collector 1 (flat part)
Step 9	All the above & Duct Top
Step 10	All the above & Duct Bottom
Step 11	All AIC elements

The results of this simulation sequence are plotted in Figure 6.13 (left). For comparative reasons, the theoretical curve obtained through simple addition of the efficiency improvement values for the distinct components (see Figure 6.9 (left) and Figure 6.10) is also plotted.
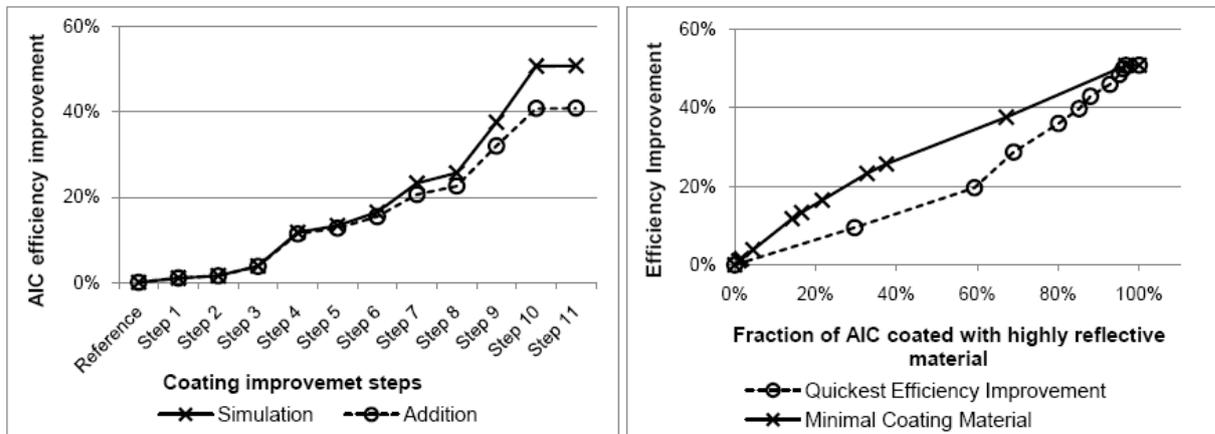

Figure 6.13 : Obtained efficiency improvement for each of the steps listed in Table 6.7 (left). Difference between the two improvement sequences "Quickest Efficiency Improvement" and "Minimal Coating Material" (right).

6.3.4 Discussion

The results displayed in Figure 6.9 (left) illustrate the enormous potential of highly reflective coating materials (such as MiroSilver™) in daylighting applications: increasing the coating material's total reflection by 8.9 % (i.e. from 90% to 98%) leads to a relative efficiency improvement of more than 50% in the AIC. The "Duct" has the highest potential for efficiency improvement, followed by the "Collector" and the "Distributor". The reason for this distribution between "Duct", "Collector" and "Distributor" lays principally in the large sizes of the "Duct Top" and the "Duct Bottom", compared to the rest of the AIC (see Table 6.6).

Figure 6.9 (right) and Figure 6.10 show that the AIC elements "Duct Top", "Duct Bottom", "Anidolic Collector 1", "Anidolic Distributor" and "Anidolic Collector 2" have the highest potential for efficiency improvement. As a matter of fact, coating only these five AIC elements with MiroSilver™ yields already 80% of the overall possible efficiency increase (i.e. efficiency increase of 40%, see Figure 6.11). This means that, if one's objective is to achieve a sound efficiency improvement by coating a minimum number of AIC elements with a highly reflective coating (Quickest Efficiency Improvement), those five AIC elements would be a very good choice. This choice does, nevertheless, not correspond to the optimal coating decision from a financial point of view. If one's objective is to achieve efficiency improvement while keeping the amount of coating material (and the associated cost) as low as possible, it makes more sense to follow the improvement sequence outlined in Table 6.7, the latter being based on the surface-specific efficiency improvements of the different AIC elements shown in Figure 6.12.

Figure 6.13 (right) visualizes the difference between the two improvement sequences: when following the strategy for "Quickest Efficiency Improvement", two improvement steps (i.e. coating the Duct Top and the Duct Bottom with MiroSilver™) are sufficient for reaching a relative efficiency improvement of 20%. However, this corresponds to 60% of the overall AIC surface coated with the highly reflective material. The improvement strategy "Minimal Coating Material" makes it possible to reach a relative efficiency improvement of more than 25%, while keeping the AIC fraction coated with MiroSilver™ lower than 40%. However, eight improvement steps are needed in this case.

If we assume market prices of 25 €/kg for anodized aluminum (showing about 90% of total reflection) and 35 €/kg for MiroSilver™ (98% total reflection), material costs would equal

approximately 1750 € for an AIC fully coated with anodized aluminum versus 2450 € for an AIC fully coated with MiroSilver™ (based on 70 kg of aluminum). Coating 40% of the AIC with MiroSilver™ would correspond to a material cost increase of 280 € versus an increase of 420 € when coating 60% of the AIC surface area with MiroSilver™. This means that following the strategy for "Minimal Coating Material" rather than that for "Quickest Efficiency Improvement" offers a savings potential of 140 € per AIC.

In Figure 6.11 and Figure 13 (left), the fact that the simulated values are getting higher and higher towards the end of the simulation series compared to the values obtained through addition are probably due to synergy effects that are not taken into account when simply adding up the single improvement values displayed in Figure 6.9 (right) and Figure 6.10. This means that summing up these distinct efficiency improvement values leads to conservative estimations of the real efficiency improvement for a given combination of coated AIC elements.

6.3.5 Conclusion

In any case, coating the "Anidolic Collector 1" with MiroSilver™ instead of anodized aluminum is suggested, as it offers a considerable efficiency improvement (see Figure 6.9 (right)) together with a good surface-specific efficiency improvement (see Figure 6.12). In AICs with smaller widths (e.g. 1m instead of 5m), the potential of the AICs side elements becomes even more important, because the surfaces will remain equal while the horizontally oriented surfaces (such as "Duct Top" and "Duct Bottom") will decrease.

7 Final Conclusion

The objective of the Green Lighting project was to develop a High Performance Integrated Lighting System, based on the most recent technologies for day- and electric lighting, achieving a lighting power density that does not exceed 3 W/m^2. In this regard, we aimed to take advantage from the experience and knowledge acquired at EPFL in the domain of day- and electric lighting by the way of collaborations with partners of the lighting and construction industry. The development of this novel Integrated Lighting System was supposed to include the design, the set-up, the on-site assessment and the optimization of such a system. A secondary objective of the Green Lighting project was to analyze and discuss possibilities for using "Future Lighting Technology", such as light emitting diodes (LED) or organic light emitting diodes (OLED), in High Performance Integrated Lighting Systems.

The Green Lighting project has revealed that Anidolic Daylighting Systems (ADS) are an ideal basis for High Performance Integrated Lighting Systems. Not only are they able to provide adequate illumination (i.e. sufficiently high illuminances) in office rooms during large fractions of normal office hours, under various sky conditions and over the entire year, but they are also highly appreciated by office occupants at the condition that effective glare control mechanisms are available. As a matter of fact, occupants of the LESO solar experimental building in Lausanne judge glare-situations to be more persistent in ADS-equipped office rooms than not-enough-light-situations [Linhart and Scartezzini, 2008]. The ideas for improving glare protection in ADS-equipped office rooms that are given in Section 2 can be of great interest when it comes to designing ADS for other types of buildings in the future.

Even if Anidolic Daylighting Systems are a very good basis for energy-efficient, high-quality office lighting, complementary electric lighting installations will always be necessary. Office occupants have to be able to work also during periods of external darkness, for example in the evenings or when the sky is extremely dark (e.g. due to a thunderstorm). The challenge when designing these complementary electric lighting installations is to find solutions that

consume a minimum of electricity while creating a maximum of visual comfort. In our particular situation, where the electric lighting installations are only a back-up option for times when there is not enough daylight available, the most interesting trade-offs between energy-efficiency and visual comfort are obtained by using a combination of ceiling-mounted directly emitting luminaires with very high luminaire efficiencies (such as the "Zen3" luminaire by Tulux [Tulux, 2009]) for ambient lighting and portable desk lamps for temporary task lighting. The most appropriate lamps for the ceiling-mounted luminaires are still highly efficient fluorescent tubes. However, white LED tubes for directly replacing fluorescent tubes in ceiling-mounted luminaires have recently become available and can be considered a realistic option for the future. The most suitable light sources for desk lamps for temporary task lighting are currently compact fluorescent lamps (CFLs, also called energy-saving lamp). However, these lamps have some significant disadvantages, for example the comparably long start-up time (see Section 5.3 of this report). A possible option for the future are white LED light bulbs, which offer an instantaneous start-up and a highly elevated lifetime, but which are still very expensive and which do not yet reach the luminous efficacies of CFLs.

However, the great potential of white *LEDs* for office lighting has been demonstrated and discussed within the framework of the Green Lighting project. The great advantage of the *OLED* for general lighting applications is the fact that (in principle) lambertian emitters of very large surfaces can be created. In addition to that, it is possible to build OLED modules which are highly transparent when no current is applied to them. This possibility can be expected to offer interesting options for lighting design, such as the use of OLED layers on windows or daylighting systems. For the time being, speculating about the widespread use of such applications is nevertheless dreaming about the future. Envisaging the use of ceiling or wall-integrated OLED panels is however somewhat more realistic and such panels can be expected to become available for office lighting applications within the next few years.

As intended in the beginning of the Green Lighting project in 2006, a High Performance Integrated Lighting System with a very low Lighting Power Density has been developed over the last four years. Detailed computer simulations carried out with the software tool RELUX Vision have made it possible to identify two promising electric lighting solutions with LPDs of 3.9 W/m^2 and 3 W/m^2, respectively. In order to run in-situ tests of these solutions, a flexible ceiling-mounted rail system with movable carriages was installed in one ADS-equipped office room of the LESO solar experimental building. The 3.9 W/m^2-solution was set up on this rail system and was intensively tested in a study with twenty human subjects [Linhart and Scartezzini, 2009]. This study revealed that the 3.9 W/m^2-solution improved the subjects' performance during a paper-based task compared to the usual lighting installation in this office. The visual comfort was good and comparable to that of the usual lighting installation. In average, the test persons preferred the 3.9 W/m^2-solution over the usual lighting installation in this office. If combined with a portable desk lamp equipped with a 7 W light bulb (CFL or LED), a suitable complementary electric lighting system for the ADS already installed in the test office can be obtained. This leads to an *installed* LPD of 4.3 W/m^2. Since this complementary electric lighting system is not operating during the entire length of a normal working day (i.e. from 08:00 to 18:00), it makes sense to define an *effective* LPD (LPD$_{eff}$) :

$$ \text{LPD}_{\text{eff}} = \frac{\text{LPD}_{\text{amb}} * \tau_{\text{amb}} + \text{LPD}_{\text{task}} * \tau_{\text{task}}}{10\text{h}} \qquad \text{(Equation 8)} $$

where LPD$_{amb}$ stands for the installed LPD that results from the ambient lighting (3.9 W/m^2 in our case), LPD$_{task}$ stands for the installed LPD that results from the task lighting (0.4375 W/m^2 in our case) and τ_{amb} and τ_{task} stand for the respective average operating hours during the normal working day (10 hours length). With worst case estimations of five hours for the ambient lighting and 2 hours for the task lighting, we find an effective LPD of slightly more than 2 W/m^2. We can thus assume that, even though the installed LPD equals 4.3 W/m^2, the objective of the Green Lighting project is achieved.

It is, however, not sufficient to limit this work to the particular situation of the LESO solar experimental building in Switzerland and its small office rooms. It must also be possible to apply Green Lighting concepts to other types of office buildings at different locations. In addition to that, Anidolic Daylighting Systems must be further improved in such a way that they are capable of illuminating other office types, for example large open plan offices. The results in Section 6 of this report show an "exportation" of Green Lighting concepts to different climatic regions (e.g. Singapore) is possible and that, also in such cases, installed LPDs of less than 5 W/m^2 can be achieved. In addition to that, the performance of AICs can be further improved by using highly reflective coating materials like MiroSilver™ [Alanod, 2009].

In conclusion, the Green Lighting project successfully demonstrated that installed LPDs of less than 5 W/m^2 and effective LPDs of less than 3 W/m^2 are already possible today if efficient daylighting systems and low-energy electric lighting components are combined in an appropriate way. White LED applications can already be used in such High Performance Integrated Lighting Systems, and their potential for the future will continue to grow. OLED applications might offer interesting options for the future, but this will still take several years.

8   Acknowledgments

9   References

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10 Appendix

Appendix A: **Office Lighting Survey – LESO**

Questionnaire

Voici un questionnaire avec 21 questions. Veuillez prendre tout votre temps pour y répondre !

Merci d'avance !

Partie A - Questions concernant l'éclairage

Voici quelques questions concernant l'environnement lumineux de votre bureau. Veuillez cocher la réponse qui vous convient le plus (1 = oui, 2 = plutôt oui, 3 = plutôt non, 4 = non) :

(1)   J'aime la lumière dans ce bureau.   OUI 1 2 3 4 NON

(2)   En tout, l'éclairage de ce bureau est confortable.   OUI 1 2 3 4 NON

(3)   Ce bureau me semble trop lumineux.   OUI 1 2 3 4 NON

(4)   Ce bureau me semble trop sombre.   OUI 1 2 3 4 NON

(5)   Il n'y a pas assez de lumière pour bien effectuer les   OUI 1 2 3 4 NON
       différentes taches.

(6)   Il y a trop de lumière pour bien effectuer les différentes   OUI 1 2 3 4 NON
       taches.

(7)   La lumière est mal repartie dans ce bureau.   OUI 1 2 3 4 NON

(8)   L'éclairage de ce bureau cause trop d'ombre.   OUI 1 2 3 4 NON

(9)   Il y a des réflexions de lumière dans ce bureau qui   OUI 1 2 3 4 NON
       m'empêche de bien travailler.

(10)   Les luminaires au plafond sont trop lumineux.   OUI 1 2 3 4 NON

(11)   Ma peau apparait peu naturelle dans cette lumière.   OUI ☐1☐2☐3☐4☐ NON

(12)   J'ai l'impression que la lumière scintille dans ce bureau.   OUI ☐1☐2☐3☐4☐ NON

(13)   La lumière dans ce bureau est trop « chaude » pour un lieu de travail.   OUI ☐1☐2☐3☐4☐ NON

(14)   La lumière dans mon bureau est trop « froide » pour un lieu de travail.   OUI ☐1☐2☐3☐4☐ NON

(15)   Si je compare la situation lumineuse dans ce bureau avec d'autres bureaux dans lesquels j'ai travaillé auparavant, je dirais que la situation lumineuse ici est …

<… plutôt meilleure >   **<… plutôt pareille >**   **<… plutôt pire >**

(16)   Lors d'une journée de travail, je pourrais bien m'imaginer travailler dans cette lumière pendant …

< … moins de 2 heures >   **< … 2 à 4 heures >**   **< …plus que 4 heures >**

Partie B - Questions générales

Pour finir, encore quelques questions générales…

(17)   Mon âge :   _____

(18)   **Aujourd'hui,** j'ai passé la plupart de la journée …

<… à l'extérieur >   **<… dans un bâtiment >**   **<… ni l'un ni l'autre >**

Si vous avez répondu « …dans un bâtiment » :
Est-ce que vous avez bénéficié de beaucoup de
lumière naturelle dans ce bâtiment?

OUI 1 2 3 4 NON

Si vous avez répondu « …ni l'un ni l'autre » : Précisez, svp !

_____

_____

(19)   **Normalement**, je travaille …

<… à l'extérieur >   **<… dans un bâtiment >**   **<… ni l'un ni l'autre >**

Si vous avez répondu « …dans un bâtiment » :
Est-ce que vous avez bénéficié de beaucoup de
lumière naturelle dans ce bâtiment?

OUI 1 2 3 4 NON

Si vous avez répondu « …ni l'un ni l'autre » : Précisez, svp !

_____

_____

(20)   Je pense que nous devons tous faire un effort pour économiser de l'énergie.

OUI [1|2|3|4] NON

(21)   Je pense qu'on peut économiser beaucoup d'énergie en utilisant un minimum de lumière artificielle.

OUI [1|2|3|4] NON

Merci de votre participation!