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HIGH PERFORMANCE INTEGRATED LIGHTING SYSTEMS: RECENT ACHIEVEMENTS WITHIN THE FRAMEWORK OF THE "GREEN LIGHTING"-PROJECT

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ABSTRACT

The „Green Lighting" project (LESO-PB/EPFL and Swiss Federal Office of Energy) explores different ways to combine advanced day- and artificial lighting technologies for achieving highly energy-efficient office lighting scenarios. This communication gives an overview of recent achievements within the framework of the project, in particular in terms of visual comfort in office rooms equipped with Anidolic Daylighting Systems (ADS), minimization of lighting power density, possible use of novel light sources such as light emitting diodes (LEDs) and possibilities to generalize these results.

It could be shown that occupant satisfaction in the considered ADS-equipped office rooms is very good and can even be optimized by a more sophisticated glare management. Lighting power densities well below 5 W/m² are already achievable today, in different types of office rooms and at various locations, provided that daylight is used intensively (for example through facade-integrated ADS). White LEDs will offer interesting options for office lighting scenarios once they reach luminous efficacies of 80 lm/W and once appropriate luminaires become widely available.

INTRODUCTION

The „Green Lighting" project, launched in 2006 at the Solar Energy and Building Physics Laboratory (LESO-PB) of the Swiss Federal Institute of Technology in Lausanne (EPFL) with the support of the Swiss Federal Office of Energy (SFOE), explores different ways to combine advanced day- and artificial lighting technologies. The main objective of the project is the development of energy-efficient integrated solutions which minimize the electric lighting load while maximizing the building occupants' visual comfort and wellbeing. These developments are based on Anidolic Daylighting Systems (ADS) [1], which are highly efficient daylighting systems based on the theory of non-imaging optics [2]. Different integrated systems were set up in an office room within the LESO solar experimental building and monitored for different periods of the year.

This communication gives an overview of recent achievements within the framework of the project. In particular, we discuss occupant satisfaction in office rooms equipped with ADS [3], ways to minimize the artificial lighting power density in such office rooms [4] and the possible ways to extend the results of the Swiss „Green Lighting" project to different office rooms (such as open space offices) and other countries [5]. Furthermore, we discuss the possibility to use light emitting diodes (LEDs) for office lighting applications [6].

OCCUPANT SATISFACTION IN ADS-EQUIPPED OFFICE ROOMS

The use of daylight (issued from the sun and the sky vault) for illumination purposes inside office buildings is a key element to energy-efficient office lighting. However, electricity savings do not come automatically with the *installation* of a sophisticated daylighting system. Lighting load reduction can only be ensured if the building's occupants *accept* and agree to *properly use* this system. If, for example, building occupants override a sophisticated daylighting system by simply closing the window blinds and switching on electric light in order to avoid glare related problems, then all effort is wasted. One main concern of architects and engineers should therefore be to develop daylighting systems that are easy to use and that allow the occupants to create a comfortable luminous environment within their office at all times.

The southern façade of the LESO solar experimental building (LESO building), located on the EPFL campus in Lausanne, is equipped with a given type of ADS [3, 7]. In order to get an insight into the occupants' satisfaction and well-being when working within office rooms equipped with this type of façade-integrated system, a detailed post-occupancy satisfaction assessment (based on questionnaires and personal interviews) has recently been carried out amongst 23 building occupants [3]. The objective of this study was not only to find out "whether occupants are satisfied with their office lighting or not", but also to identify weak spots in the lighting installation (e.g. within the ADS itself or the associated control system) and to find solutions for eliminating them.

This satisfaction assessment clearly showed that the ADS installed within most offices of the LESO building are in general very well accepted by the 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 problems are caused by temporary daylight overprovision within the offices. Figure 1 gives an overview of the main problems and quantifies how annoying they are to the occupants (mean annoyance values calculated according to [3], where 100% signifies "totally annoying" and 0% signifies "not annoying at all").

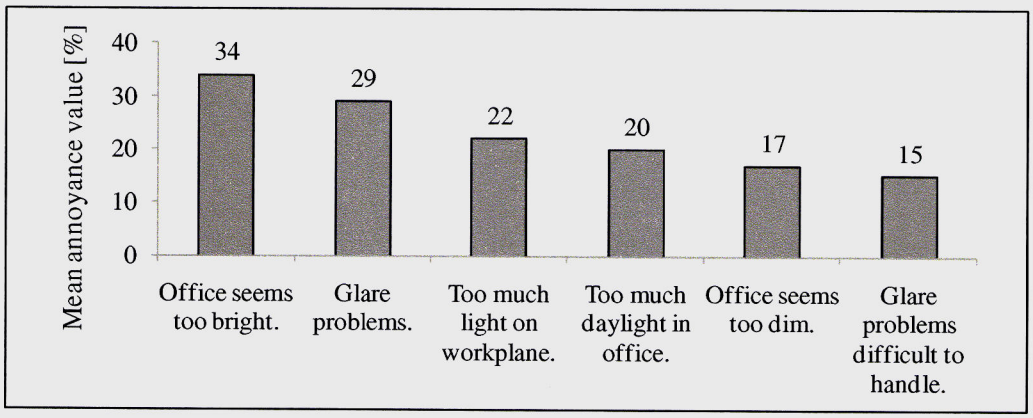

Figure 1: Overview of the main lighting related problems within the examined ADS-equipped office rooms. Annoyance values are in general quite low, and most problems are due to temporary daylight-overprovision, resulting from inappropriate blind configuration and control, as well as problems with ADS handling.

We were able to conclude that the annoyance of most problems revealed during our study could be drastically reduced by optimizing the blind configuration and related control as well as by giving introductions on how to properly handle the ADS to the building's occupants. If such systems could be optimized in this regard, they have indeed a large potential for becoming the basis of future energy-efficient office lighting designs.

MINIMIZATION OF LIGHTING POWER DENSITY

As explained in the previous section, optimized 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 natural lighting 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), but we believe that it is 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 the powerful 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 normal office hours (from 8:00 to 18:00, with some exceptions).

One very simple but yet extremely effective way to reduce the electric lighting load of an office building is to minimize the lighting power densities (i.e. the connected lighting power in an office room divided by the corresponding floor area), also referred to as LPDs. During a study carried out in the LESO building from April to June 2008 (comparable to a study previously described by Page et al. [8]), two different low-LPD lighting designs (4.5 W/m^2, current best practice in LESO building and very much appreciated by the occupants, vs. 3.9 W/m^2, new lighting design) were compared [4]. Twenty persons were asked to perform various tasks at a workplace situated in an office room with a ceiling mounted quick positioning system for luminaires. The test persons' performance (during a screen-based [9] and a paper-based task), their subjective visual comfort (questionnaire-based office lighting survey [10]) as well as their subjective alertness (Karolinska Sleepiness Scale) were assessed. Two important outcomes of the study (a detailed discussion of all results being far beyond the scope of this article) are presented in Figure 2.

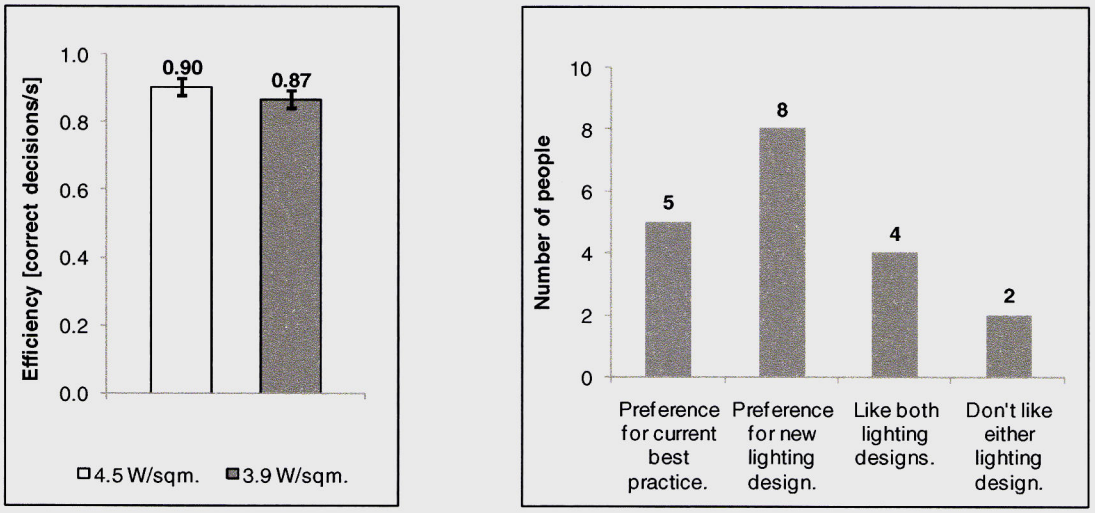

Figure 2: Visual performance (Landolt-ring test) of study subjects under the two different lighting designs (left) and subjective user preferences for the two different solutions (right).

Figure 2 (left) shows the results of a computer-based visual performance test, where the study participants had to determine the correct orientation of Landolt-rings shown to them on a VDT screen [9]. The efficiency is measured in correct decisions per second. Figure 2 (right) visualizes the fact that

around 90% of the subjects could be satisfied with one of the two low-LPD lighting designs; only 2 subjects (i.e. around 10%) didn't like either of the two solutions.

This study shows that it is possible to reduce the LPDs in this office building down to less than 5 W/m^2 without jeopardizing the occupants' visual comfort and performance. Even reductions to less than 4 W/m^2 are feasible.

USING THE "GREEN LIGHTING"–APPROACH IN DIFFERENT CONTEXTS

During the "Green Lighting"-project, highly efficient daylighting systems and complementary low-LPD artificial lighting systems were designed for an office building. So far, we have only discussed this approach for one particular ADS (i.e. the anidolic façade element [3, 7]), one particular office type (i.e. a small office room occupied by one or two office worker(s)) and one particular daylighting climate (i.e. the Geneva lake region). However, if the "Green Lighting"-approach is to make a larger impact, possibilities to apply it to different offices with different daylighting systems situated in different climatic regions have to be discussed. This has been done within the framework of a joint project by LESO-PB/EPFL and a group of researchers at the National University of Singapore in 2007.

Wittkopf et al. had previously simulated the performance of an Anidolic Integrated Ceiling (AIC) installed in a 36 m^2 office room under Singapore daylight conditions [11]. Based on their calculated daylight autonomies for this office room, we have designed an appropriate low-LPD artificial lighting system [5]; it leads to an LPD of 4.9 W/m^2. Figure 3 gives an overview of this lighting design.

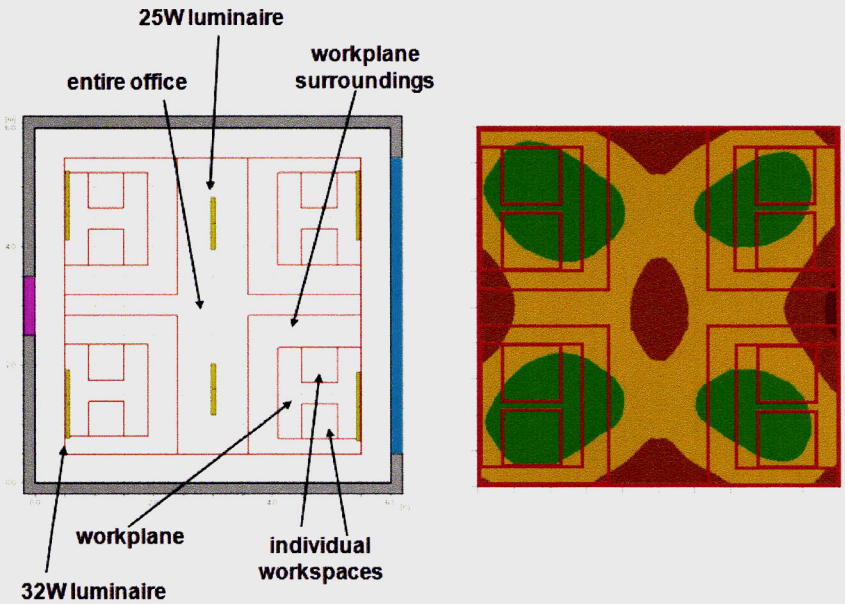

Figure 3: Luminaire positions and reference planes considered during computer simulations for the 36m^2 office room in Singapore (left) and resulting illuminance distribution at a reference height of 80 cm above floor level (right).

The resulting average illuminance varies between 230 lux and 260 lux for the different reference planes (just underneath the required value of 300 lux) and can thus be expected to be sufficient in this type of office room equipped with an AIC and abundant access to daylight. The uniformities g_1 (i.e. the lowest illuminance value measured on a particular reference plane divided by the corresponding mean illuminance) range between 0.6 and 0.85 for the different reference planes and are thus also acceptable.

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 design an even more energy-efficient lighting solution for this type of office room in Singapore.

WHITE LIGHT EMITTING DIODES (LEDS) FOR OFFICE LIGHTING

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.

During a 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 [6]. After identifying suitable LED products, we have used the RELUX Vision software tool for simulating energy-efficient lighting solutions based on LED technology in 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. Those luminaires were initially equipped with five white LEDs (1.2 W power consumption) and designed rather for decorative than for general lighting. During the simulations, we have gradually increased those luminaires' output flux to values between 60 lm/w and 100 lm/W. We were able to show that, if used in such a way, white LEDs would become a real alternative to replace fluorescent lighting solutions once they reach luminous efficacies of 80 lm/W. Figure 4 shows the simulation of a corresponding 3.25 W/m^2-lighting design for a LESO building office room. A combination of eight Altea LED Bianco luminaires and two additional high power LEDs (OSRAM) installed right above the individual workspaces was used. The resulting illuminance distribution at a reference height of 80 cm above floor level is shown in Figure 4 (left) whereas Figure 4 (right) shows the positioning of the LED luminaires on the office room's ceiling (if luminaires are not pointing vertically downwards, this has been indicated by means of directional arrows). The different reference planes (i.e. entire office, workplane surroundings, workplane and two individual workplaces) are indicated by red rectangles.

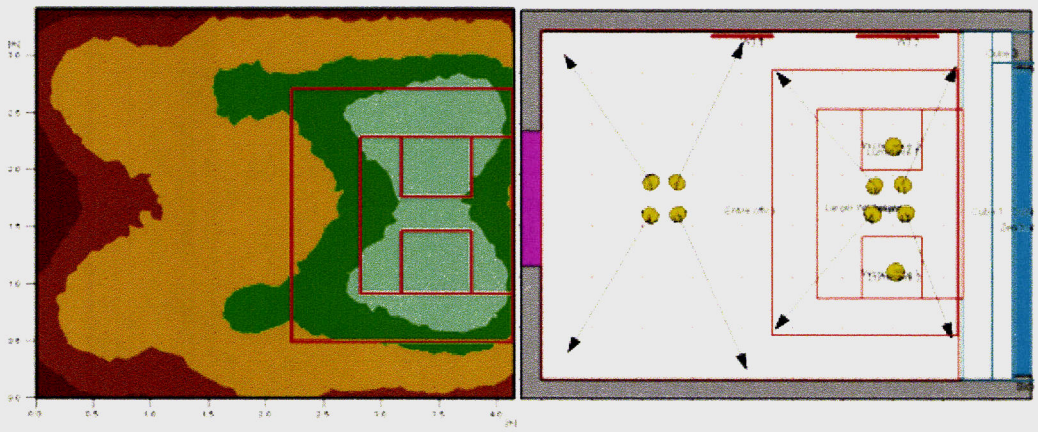

Figure 4: Resulting illuminance distribution for the LED-based lighting design at a reference height of 80 cm above floor level (left) and positioning of the LED luminaires on the office room's ceiling (right).

Figure 5 shows the resulting average illuminances and uniformities g_1 for the lighting design shown in Figure 4. The obtained illuminance values are comparable to those tested by Linhart and Scartezzini in 2008 [4], the uniformities being reasonably good. The lower value for the reference plane "entire office" are due to very low illuminances near the door, but this might not be too annoying to office

workers. In any case, this simulated lighting design is an interesting situation to test in a future study within our test office room in the LESO solar experimental building.

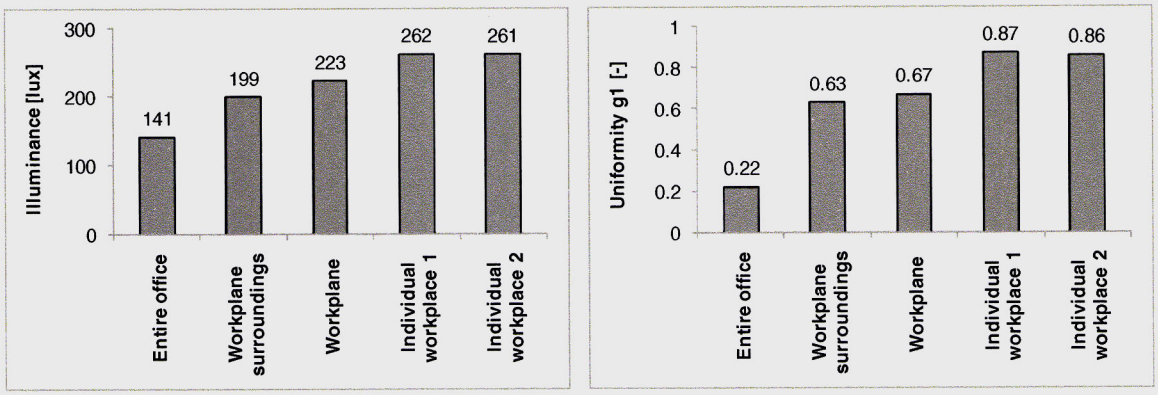

Figure 5: Resulting average illuminances and uniformities g_1 (i.e. the lowest illuminance value measured on a particular reference plane divided by the corresponding mean illuminance) for the LED lighting design (cf. Figure 4).

CONCLUSION

It was shown during this project that occupant satisfaction in the considered ADS-equipped office rooms is very good and can even be optimized by a more sophisticated glare management. Lighting power densities well below 5 W/m² are already achievable today, in different types of office rooms and at various locations, provided that daylight is used intensively (for example through facade-integrated ADS). It can also be pointed out that white LEDs will offer interesting options for office lighting scenarios once they reach luminous efficacies of 80 lm/W and more. They have large potential for becoming a real alternative to fluorescent lighting when more appropriate LED luminaires become available.

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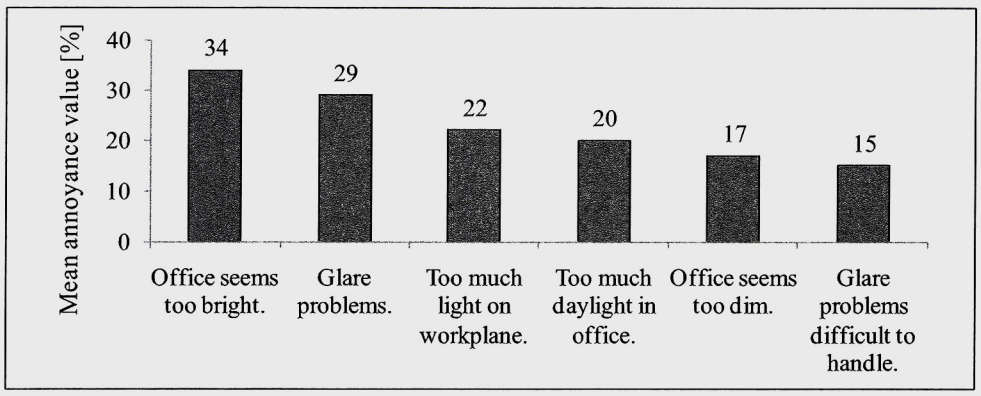

Figure 1: Overview of the main lighting related problems within the examined ADS-equipped office rooms. Annoyance values are in general quite low, and most problems are due to temporary daylight-overprovision, resulting from inappropriate blind configuration and control, as well as problems with ADS handling.

We were able to conclude that the annoyance of most problems revealed during our study could be drastically reduced by optimizing the blind configuration and related control as well as by giving introductions on how to properly handle the ADS to the building's occupants. If such systems could be optimized in this regard, they have indeed a large potential for becoming the basis of future energy-efficient office lighting designs.

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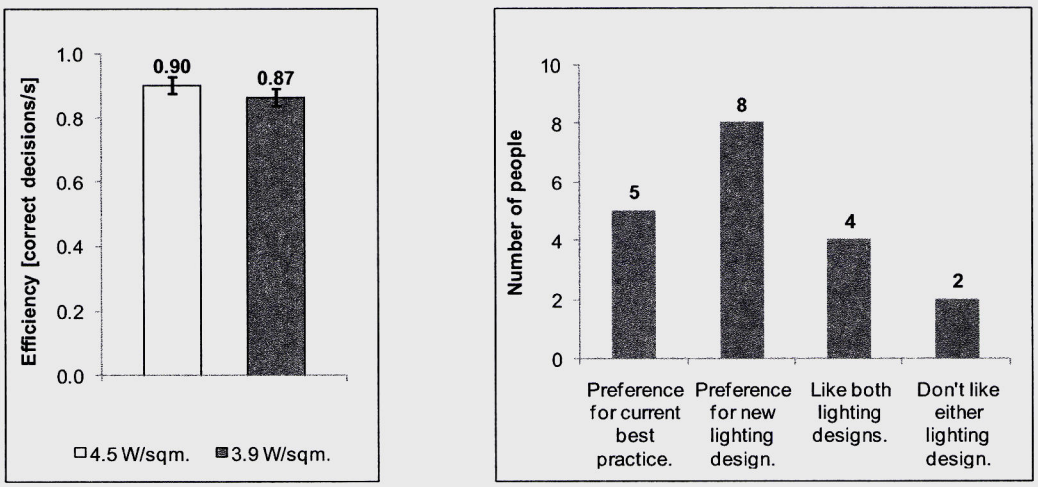

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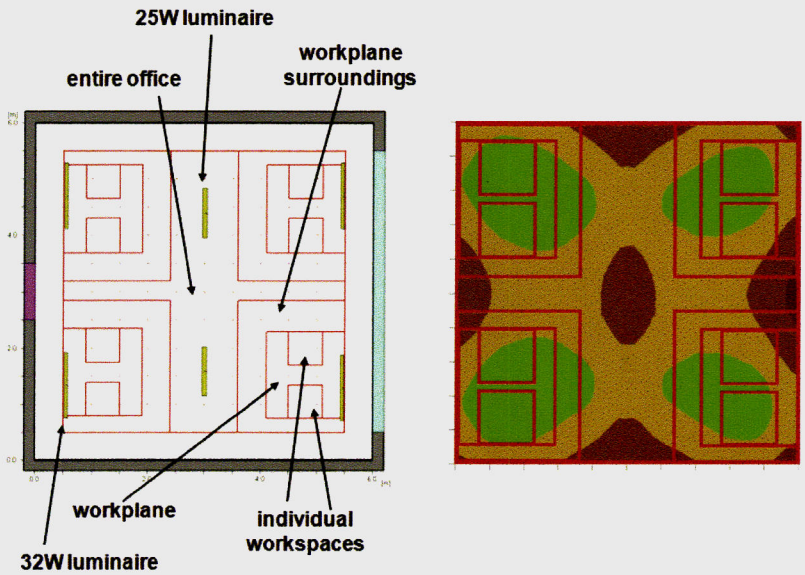

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g_1 (i.e. the lowest illuminance value measured on a particular reference plane divided by the corresponding mean illuminance) range between 0.6 and 0.85 for the different reference planes and are thus also acceptable.

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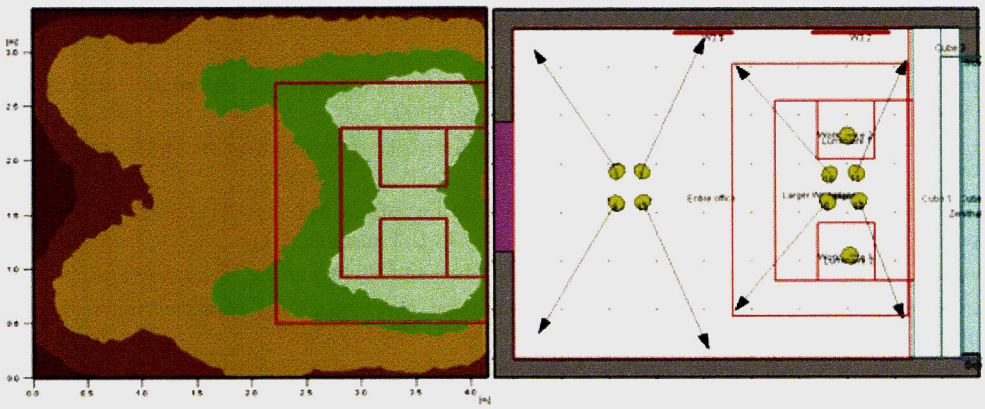

Figure 4: Resulting illuminance distribution for the LED-based lighting design at a reference height of 80 cm above floor level (left) and positioning of the LED luminaires on the office room's ceiling (right).

Figure 5 shows the resulting average illuminances and uniformities g_1 for the lighting design shown in Figure 4. The obtained illuminance values are comparable to those tested by Linhart and Scartezzini in 2008 [4], the uniformities being reasonably good. The lower value for the reference plane "entire office" are due to very low illuminances near the door, but this might not be too annoying to office workers. In any case, this simulated lighting design is an interesting situation to test in a future study within our test office room in the LESO solar experimental building.

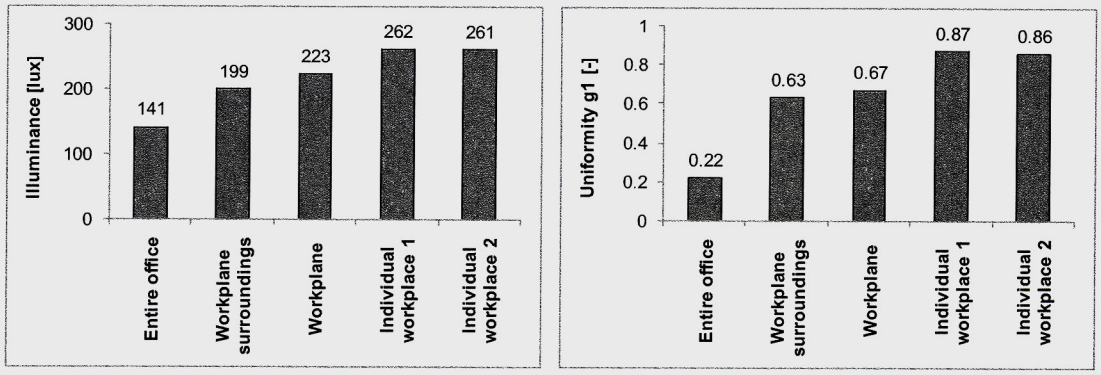

Figure 5: Resulting average illuminances and uniformities g_1 (i.e. the lowest illuminance value measured on a particular reference plane divided by the corresponding mean illuminance) for the LED lighting design (cf. Figure 4).

CONCLUSION

It was shown during this project that occupant satisfaction in the considered ADS-equipped office rooms is very good and can even be optimized by a more sophisticated glare management. Lighting power densities well below 5 W/m² are already achievable today, in different types of office rooms and at various locations, provided that daylight is used intensively (for example through facade-integrated ADS). It can also be pointed out that white LEDs will offer interesting options for office lighting scenarios once they reach luminous efficacies of 80 lm/W and more. They have large potential for becoming a real alternative to fluorescent lighting when more appropriate LED luminaires become available.

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