# Energy Efficiency Lighting for Buildings – Experiments on occupant behavior and visual comfort on a test bed in a university campus office

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## ABSTRACT

How much electricity lighting system consumes is up to number of factors, for instance architecture design, glazing specifications, light source, and so on. In order to improve lighting efficiency even more, proper control strategies are necessary to be applied. In which occupant behavior and visual comfort perception have to be considered at the same time.

This article is about a study on energy performance of various lighting systems and control strategies applied in open-plan offices. All the experiments were carried out on a test bed which is located on Tongji University, Shanghai. This test bed can realize various control strategies, including daylight linked dimming control and on/off control by occupancy detection. Data of illuminance and power is monitored, displayed and recorded automatically by an online data acquisition system. Online tests were conducted on various lighting control strategies for a period of time and the energy use is compared to that of the lighting system in the baseline office. The energy saving potential of various lighting control strategies is simulated and analyzed. Moreover, a combined lighting control strategy - background dimming lighting + task lighting is studied on the test bed. Occupant behavior and visual comfort are investigated in order to find out the optimal background dimming lighting illumination and energy performance of the combined lighting system is evaluated.

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## INTRODUCTION

According to statistics (Halonen et al. 2010), 19% of the global electricity consumption is created by more than 33 billion lamps worldwide. Meanwhile artificial lighting is also a heat source, which causes cooling loads. Therefore energy saving in lighting system could be very important for reduction of building energy consumption, especially in cooling dominant regions. High-efficiency lighting system and intelligent lighting control might be the right way to save energy use of lighting.

The test bed is located in an office building in the university. DALI controller, connector, switch, dimming electronic ballast and efficient luminaires from OSRAM are installed in one office to replace original lighting system and another office which is the same as the test bed in previous layout and illumination installation, is selected as the reference baseline office for comparison. An online monitoring system is installed to measure, display and record the performance of the test bed automatically. The special focus is on intelligent lighting controls in combination with highly efficient light sources and luminaires.

In order to maximize energy saving potential of lighting system in the test bed, task lighting is applied to accomplish a more comfort and flexible illumination scenario. With task lighting, occupant can adjust local illuminating environment and avoid adjustment of large scale background lighting. A survey of percent of occupant satisfaction is conducted to identify the most energy efficient combination of background illumination and task-lighting intensity, which doesn't affect occupant satisfaction of visual perception.

This paper presents the design and development of the test bed, and the online test results of lighting power under various lighting control strategies. This study can support the applications in engineering and to underlie exact lighting control strategy for diverse building types and use-pattern of office. Furthermore, strategy presented to combine dimmable background lighting and task-lighting efficiently is applicable for most open-plan offices.

## PRE-STUDY OF ORIGINAL OFFICE LIGHTING SYSTEM

The 15m×15m office where the test bed is installed is located on the west corner of the 8th floor in an office building, with both the southwest and northwest façade sunlit with windows. The office has 3 spaces: an open-plan office, a meeting room and a personal office (**Figure 1**). The location of each lamp is shown in **Figure 2**. All of the lamps in the office can be switched on/off manually in groups.

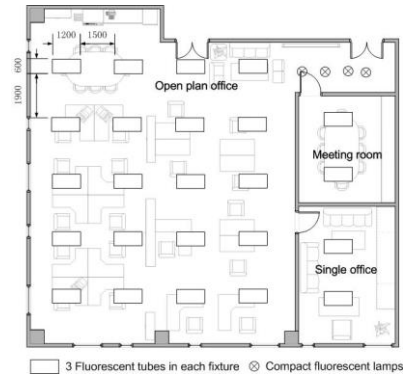**Figure 1**.*Office plan and testing points*



**Figure 2**. *Locations of lamps*

The light power density (LPD) is 12.5W/m$^2$, excluding the power of ballasts, which is higher than the LPD specified by Design Standard for Energy Efficiency of Public Buildings (MOHURD 2005) – 11 W/m$^2$, and therefore shows obvious energy-saving potential.

The illuminance measurement result shows the illuminance on the desk top meets the requirement of the Chinese standard, which is 300lux for normal office.

## DESIGN AND INSTALLATION OF TEST BED

### Lighting system on test bed

On the test bed, T5 fluorescent lamps replaced the old 36 W tubes, so the LPD is reduced from 12.5W/m$^2$ to 9.8W/m$^2$. Only with manual control as before, we can see a lighting power reduction of 20% by replacement without any better control.

The lamps in open-plan office are controlled in 4 groups with one DALI MULTI 3 controller for each group and 1~2 combined sensors, which can measure both occupant signal and illuminance. The individual office has the same system. In the meeting room a rotary knob is used for dimming and on/off switch.

In Table 3 we list all preset control modes in DALI MUTI 3 that are tested. Luminaires are controlled independently in each group and no signal is shared among different control groups.

For task-lighting investigation, a desk lamp is installed on each desk for occupant use.

**Table 1**. *Preset control strategies in controller DALI MULTI3 (OSRAM 2007)*

| No. | Occupant detect | Daylight linked control | No. | Occupant detect | Daylight linked control |
|---|---|---|---|---|---|
| 1 | Enabled | Disabled | 5 | Enabled | Enabled |
| 2 | Enabled, not automatically switch on if detecting occupant motion | Disabled | 6 | Enabled | Enabled, daylight linked control according last manually selected |

| | | | | | dimming level |
|---|---|---|---|---|---|
| 3 | Disabled | Enabled, not automatically switch on with insufficient daylight | 7 | Enabled, not automatically switch on if detecting occupant motion | Enabled |
| 4 | Disabled | Enabled, not automatically switch off with sufficient daylight | 8 | Enabled, not automatically switch on if detecting occupant motion | Enabled, not automatically switch off with sufficient daylight |

## Control and data acquisition system

Following instruction (Osram, 2003), we put 6 sensors in the office to ensure no blind area exists. **Figure 3** illustrated grouping of lamps, controllers and sensors.

Task lighting is controlled locally. 4-stage luminance level is manually adjustable.

Monitored data include illuminance and power. Only illuminance in Room 801 (test bed) is measured and recorded by illuminance sensors. These sensors are installed next to OSRAM sensors. Two more sensors are attached on the inside surfaces of northwest and southwest windows, to measure the illuminance caused by window transmitted sunlight, which is regarded as effective outdoor illuminance.

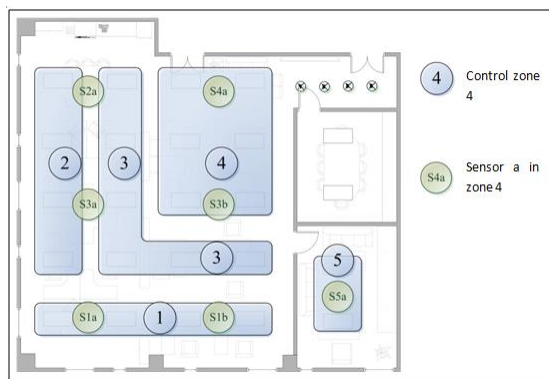Lighting power and energy use in both offices are monitored by power meters.



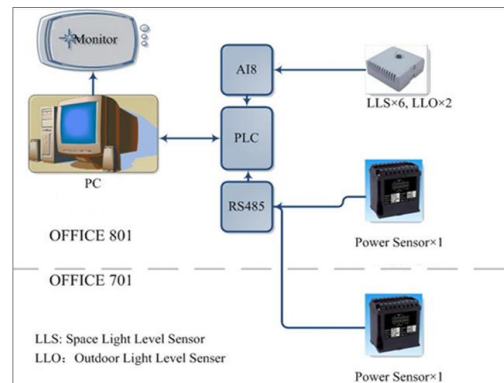***Figure* 3**.*Control zone and responsible sensors*



***Figure* 4**.*Schematic of monitoring system*

Data gathering core is a PLC, which collects all input signals and then sends measured data immediately to a PC. Monitored data are stored in a database and visualized on the screen of PC (**Figure 4**).

## GENERAL LIGHTING CONTROL STRATEGY

Available lighting control` strategies preset in the controllers are listed in **Table 1**. The lighting system operates one week under each strategy. The testing period lasts from Aug.22, 2011 to Oct.30, 2011. P801 and P701 represent for lighting power in Room 801 and Room 701 respectively.
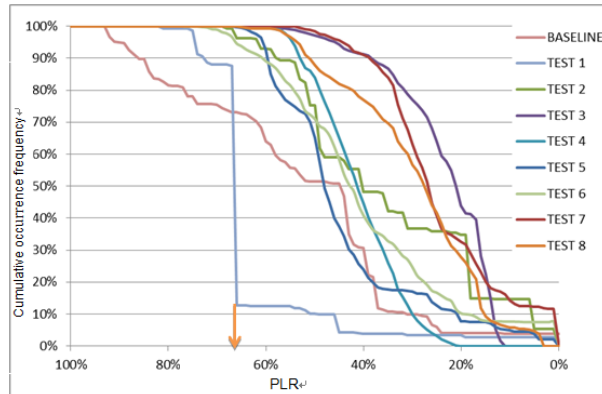


***Figure 5*** .  *Accumulative occurrence of PLR under different control strategies*

**Figure 5** illustrates cumulative frequency of power percentage occurrence under all of the 8 control strategies. The horizontal axis represents the percentage of the actual power at one moment in the installed power. This percent could also be called as partial load rate (PLR). The vertical axis represents the proportion of period that the power is below a certain value, to the entire working period.

The pink curve shows that in the baseline office higher PLR occurs in longer period of time, which indicates higher lighting power and energy use. With less than 80 % of the total power, only in 80 % of the operation lighting needs are met. In contrast, the curve close to the minimum of its vertical axis, stands for a lower loading rate that lighting system works with a lower intensity within a greater proportion of working hours. Therefore the strategy 3 and 7 should be the lowest energy consumption strategy.

The curve shape of TEST 1 is different from the others, with a dramatic decrease at 67% PLR. It indicates that the lighting system operates under PLR of 67% during most of the working period.

The relative energy saving ratio for each strategy is calculated with this formula:

Ralative Energy Saving Ratio

$$= 1 - \frac{\dfrac{\text{Lighting energy use in test bed}}{\text{Installed lighting power in test bed}}}{\dfrac{\text{Lighting energy use in baseline office}}{\text{Installed lighting power in baseline office}}} \qquad (1)$$

***Table 2*** *Energy saving ratio and relative energy saving ratio of various control strategies*

| Test No. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Energy save | kWh | -21 | 21 | 43 | 6 | 8 | 29 | 35 | 18 |
| Energy saving ratio | % | -54.2 | 38.0 | 65.3 | 13.6 | 16.6 | 42.6 | 59.9 | 39.5 |
| Relative energy saving ratio | % | -63.7 | 34.3 | 63.2 | 8.3 | 11.5 | 39.1 | 57.4 | 35.8 |

TEST 3 and TEST 7 have the best energy saving performance in the corresponding office. Excluding impact by unstable human behavior, an electricity saving rate could reach 50% or even higher. Considering risk of lamps left on for all night, mode 7 with enabled motion/occupants detection is recommended.

## TASK LIGHTING CONTROL STRATEGY

### Test Plan
4 scenarios of general lighting are investigated. In each scenario, general lighting illuminance is preset and fixed to 75lx/100lx/150lx/200lx, respectively. Then the occupants are asked to adjust their desk lamp luminance to the most comfortable level. With the target work-plane-lighting-level of 300lx, actual lighting level is measured after all the occupants finish lighting adjustment.

5 most relevant indicators based on previous study (Cai et al 2013) are selected to form subjective evaluation survey: Glare, Definition, Proper luminance contrast, Color rendering, Pleasure. Each indicator is evaluated to 4 levels. Analytic Hierarchy Process (AHP) is used to identify weighting factor of each indicator. General Satisfaction Level is used to evaluate each scenario and it's calculated as:

$$F=0.3707Y_{glare}+0.2156Y_{definition}+0.1688Y_{luminance\ contrast} \qquad (2)$$
$$+0.1488Y_{color\ rendering}+0.0961Y_{pleasure}$$

where F is calculated General Satisfaction Level and Y is individual indicator evaluated level.

### Occupant Behavior in Adjusting Lighting Environment
Test result is shown in **Table 3**. When the adjustment is finished, Objective Evaluation Survey is conducted. F of 3 is defined as "Satisfied" (**Figure 6**). Only if more than 85% subjects felt the lighting environment satisfied, the corresponding lighting scenario is qualified to be an optimal option.

***Table 3*** *Statistic of Task Lighting Status in 4 scenarios*

| Scenario | General lighting level | Usage Ratio | | | |
|---|---|---|---|---|---|
| | Lx | 100% On | Dim To 50% | Dim To 20% | Off |
| N1 | 75 | 7.35% | 80.03% | 12.62% | 0.00% |
| N2 | 100 | 6.37% | 42.66% | 50.97% | 0.00% |
| N3 | 150 | 2.91% | 24.76% | 72.33% | 0.00% |

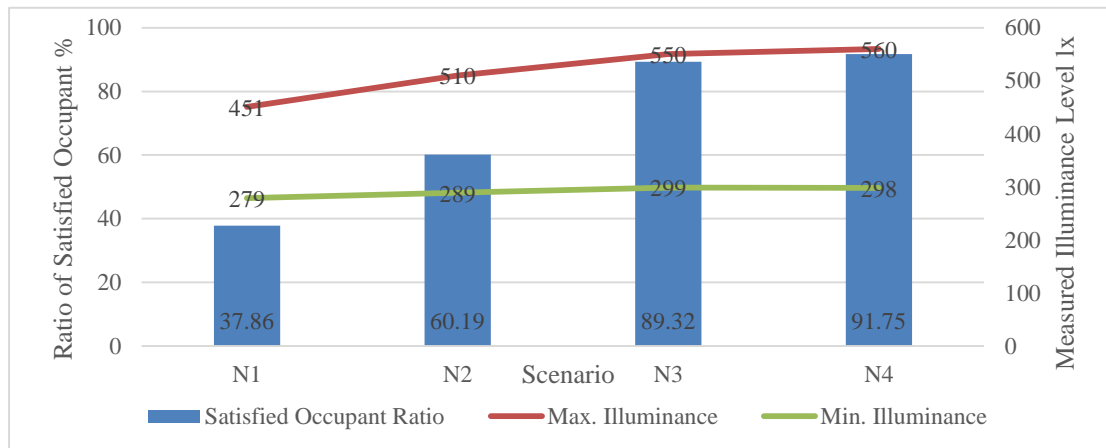| N4 | 200 | 2.91% | 17.47% | 79.12% | 0.49% |
|---|---|---|---|---|---|



***Figure 6.** Result Statistic of Subjective Evaluation Survey to Visual Comfort*

**Figure 6** shows the result based on all validated samples. When narrowing down the sample range to illuminance level between 355lx and 380lx, the ratio of satisfied occupant rises up to 88.37%.

**Energy Saving of Task Lighting Combined with Dimmable General Lighting**
Using Daysim to simulate annual Daylight Autonomy and export the result to EnergyPlus, the energy saving potential of task lighting+ daylight-linked dimmable general lighting can be estimated (Table 4).

*Table 4 Estimated Annual Energy Saving Rate of Various Lighting Control Strategy*

|  | General Lighting A（kWh） | General Lighting Dimming B（kWh） | General Lighting Dimming+Task Lighting C（kWh） | Reduction Ratio of General Lighting Dimming (A-B)/A | Reduction Ratio of General Lighting Dimming+Task Lighting (A-C)/A |
|---|---|---|---|---|---|
| Annual Value | 3,470 | 1,886 | 1,432 | 45.65% | 58.73% |

With task lighting, energy saving rate of dimmable general lighting can be raised from 46% to 59%.

**RESULTS**
Daylighting and occupant behavior are two main factors that influence the performance of lighting system. By analyzing the test data from the test bed, the following conclusions can be drawn:
(1) Manual switching on and automatic switching off of lighting by detecting occupant motion is recommended among various control strategies.

(2) Mode 7 is most recommended way to control general lighting: occupant detect enabled, but not automatically switch on if detecting occupant motion. Daylight-linked dimming enabled, not automatically switch off with sufficient daylight.

(3) Target to 300lx on desk top, general lighting of 100lx is acceptable in term of visual comfort. It is the most energy efficient combination of task-lighting/general lighting among comfortable lighting environments.

(4) Dimmable general lighting has an energy saving rate of around 50%. Task lighting can increase it to around 60% without compromising visual comfort.

## CONCLUSION AND IMPLICATIONS

Daylight-linked dimming and occupant-detecting on/off control both has a high potential in lighting energy saving. Together with individual adjustable task lighting, a combined energy saving rate can reach 60%. However, optimizing energy efficiency should not sacrifice satisfaction level of occupant perception. Therefore, though lower the general lighting intensity is, the less energy lighting system will consume, decrease of general lighting should be limited. Otherwise, uncomfortable glare, high luminance contrast and other predictable comfort issues will show up with too low general lighting level.

## ACKNOWLEDGEMENTS

## REFERENCES

Halonen, L. Tetri, E. and Bhusal, P. 2010. Guidebook on Energy Efficient Electric Lighting for Buildings, Aalto University School of Science and Technology.

OSRAM. 2007. Operating instructions: DALI MULTI 3 - Control unit. IV / 2007 ed. 2007.

OSRAM. 2003. Installation instructions: Light and motion sensor LS/PD MULTI3. I/2003ed. 2003.

MOHURD, 2005. GB 50189-2005 Design Standard for Energy Efficiency of Public Buildings.

Cai, D. Pan, Y and Huang, Z. 2013. Study of Objective Evaluation Indicators for Visual Comfort in Office, Building Energy Efficiency.