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

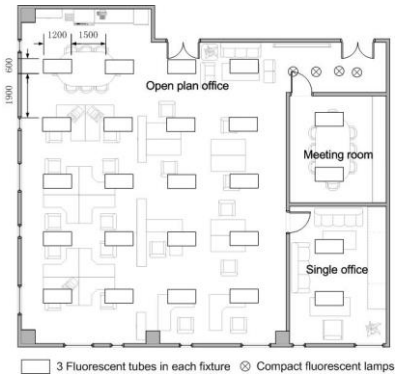

***Figure 2**. Locations of lamps*

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
1	Enabled	Disabled
2	Enabled, not automatically switch on if detecting occupant motion	Disabled

No.	Occupant detect	Daylight linked control
5	Enabled	Enabled
6	Enabled	Enabled, daylight linked control according last manually selected

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.

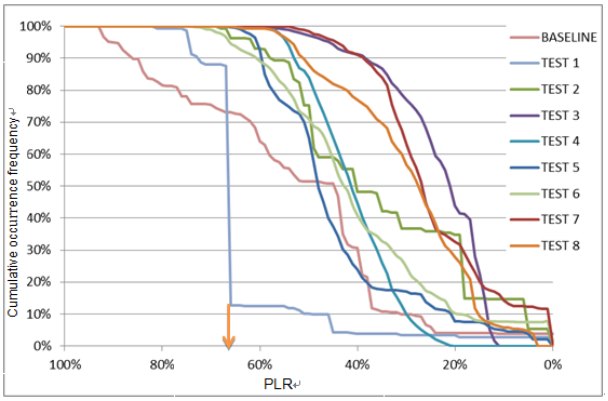

Figure 5. *Accumulative occurrence of PLR under different control strategies*

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:

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

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%

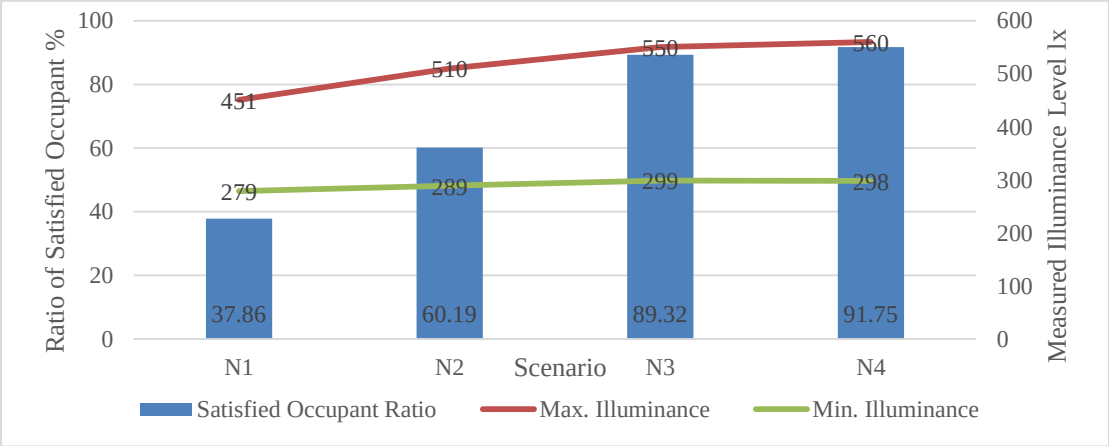

Figure 6. *Result Statistic of Subjective Evaluation Survey to Visual Comfort*

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

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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.