Development of a Rotatable Outdoor Testbed and the Testing of an Integrated Auto-dimming Lighting and Automated Blind System in the Tropics

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ABSTRACT

To drive the research and development of energy-efficient building technologies in the tropics, an advanced rotatable testbed, BCA SkyLab, was developed in Singapore in collaboration with Lawrence Berkeley National Laboratory (LBNL). As world's first high-rise rotatable testbed for the tropics, this facility is an outdoor testbed sitting atop a 7-storey building, with a rotatable platform that can simulate various orientations of building. The testbed allows testing and evaluation of performance of various technologies in the tropical urban environment, including lighting, air-conditioning, facades, shades and control systems. Performance in visual comfort and potential in deeper energy savings of an integrated auto-dimming lighting with automated blinds system was investigated in the SkyLab. This system was installed and tested together with a conventional baseline system in the two cells in the SkyLab. This integrated system uses auto-dimming control based on outdoor illuminance level through the Digitally Addressable Lighting Interface (DALI), and the automated blinds incorporates a two-section daylight-redirecting design to introduce maximum daylight while minimising Daylight Glare Probability (DGP). The system performance of energy savings and visual comfort were investigated with an innovative control algorithm developed in-house. It was found that the automated blinds effectively eliminated glare discomfort, and with the automated blinds working in conjunction with the auto-dimming, up to 74% of lighting energy savings is achievable without compromising the illuminance level at the working plane.

Keywords: *auto-dimming, automated blinds, daylight redirecting*

1. INTRODUCTION

Lighting system with automatic dimming is gaining popularity as a green building technology. Studies have shown high potential for lighting energy savings by automatic dimming system when sufficient daylighting is available. Galasiu et al. (2007) reported 10-20% savings by using daylight-linked dimming over one year in an office building located in Burnaby, Canada. Fernandes et al. (2014) found that daylighting-based dimming controls integrated with set point tuning can reduce lighting energy by about 20%, compared to the recommended 12 W/m^2 in ASHRAE 90.1-2007 for day-lit zones in New York Times Headquarters Building. Delvaeye et al. (2016) reported that 46% of lighting energy savings can be achieved by an open loop system with Digitally Addressable Lighting Interface (DALI) control in an one-year measurement conducted in a classroom in Belgium. These studies used either T5 or T8 fluorescent lamps. Switching from florescent lighting (e.g., T5 and T8) to LED could also bring energy savings, as some studies showed. A study conducted in an eight-story office building in the UK (Department of Energy & Climate Change, 2014) reported 30% of electricity savings due to replacement of T5 lighting with LED lighting and upgraded BMS system. Richman et al. (2011) conducted a laboratory evaluation of LED and T8 lamp products, and reported that 3-24% of lighting energy savings can be achieved by LED depending on fixture type, compared to T8.

Window blinds system is usually used in conjunction with indoor lighting system to modulate daylight and reduce glare. The lighting and blinds systems may operate independently or as an integrated system. Lee et al. (1998) performed a full-scale test bedding of an automated Venetian blind with T8 dimmable lighting system in two unoccupied, private offices in Oakland, California. For an office with Southeast-facing façade, 1 – 22% lighting energy savings can be achieved by the dynamic system (automated blinds plus auto-dimming lighting), compared to fixed blinds partly closed at 15o with auto-dimming lighting. Daily lighting energy savings of 22-86% were obtained with the dynamic system compared to a static system (fixed blind set at any tilting angle plus non-dimmable lighting). Lee et al. (2009) conducted another experimental study in an 88.4-m^2 window system testbed facility located at Lawrence Berkeley National Laboratory (LBNL). A system consisting of automated daylight-redirecting blinds and auto-dimming lighting saved 69% of lighting energy comparing to a system with manually-operated Venetian blind and non-dimmable lighting. These savings are based on an average daytime of 6 am – 6 pm. Mettananta & Chaiwiwatworakul (2014) reported that more than 24% of lighting energy savings can be obtained from a system consisting of auto-dimming lighting and automatic vertical blinds in a laboratory room with North-west facing façade in Thailand. Chaiwiwatworakul et al. (2009) reported a lighting energy saving of 80% in an office building in Thailand, which is equipped with an automated blinds system and an auto-dimming ballast lighting system with an optimized operation scheme developed through simulations.

Lighting energy savings by daylight-responsive auto-dimming and automated blinds system can be affected by a few factors: 1) daylight availability affected by location and orientation, and 2) shading configurations including type, material, control strategies, etc. This study investigates the performance of an integrated system consisting of auto-dimming lighting and automated blinds. The automated blinds system is a split system with the top part featuring daylight re-directing functionality and the bottom part for glare control. Experiments were conducted in the newly established BCA SkyLab facility, which is a rotatable outdoor test bed subjected to the tropical climate in Singapore. The facility has two side-by-side, identically configured test compartments with interior simulating an office environment facilitating well-controlled comparative studies. The results shall provide new insights into the operational characteristics and energy savings potentials of an integrated auto-dimming lighting and auto blind system in the tropical context.

2. METHODOLOGY

2.1 Configuration of the BCA SkyLab test facility

The test facility is constructed on an outdoor 360o rotatable platform enabling tests to be carried out at any orientation under the exposure to real weather conditions. In addition, it adopts a plug-and-play concept, allowing quantitative assessment of technologies in individual or combined configurations. The facility is situated atop a 7-storey-tall building to avoid shadow casted by neighbouring buildings. The facility has two configurable test compartments (the reference cell and the test cell) side-by-side and a control room located behind the test compartments. The two compartments are identical in dimensions (8.41 m L × 5.54 m W × 3.47 m H) and orientation, enabling comparative studies of the performance of design solutions and technologies in the test cell against a baseline setup in the reference cell. The control room holds the Building Management System (BMS), data acquisition system (DAQ) and other monitoring systems.

The exterior walls are built from 257-mm-thick aluminium composite panel and plasterboards with insulations. The U-value of the exterior wall is 0.2 W/m^{2}K. One of the sidewalls is a full-height window façade. The window is made of double-pane low-E glazing with aluminium frame and thermal block insulation. The window façade has a U-value of 1.54 W/m^{2}K and a shading coefficient of 0.30. The roof is made of 100-mm-thick concrete slab and 50 mm of ultra-foam insulation. The floor is carpeted. There are 4 typical office work stations in each cell. A thermal dummy (0.3 m in diameter and 1.1 m tall) made from galvanised steel sheet is put at the seat position of each work station. Each thermal dummy is providing up to 180 W of sensible heat. Each cell is served by a fan coil unit (FCU) with an indoor temperature set point of 22°C. Indoor relative humidity is maintained at 65%. Figure 1 (a) shows the schematics of the experimental setup.

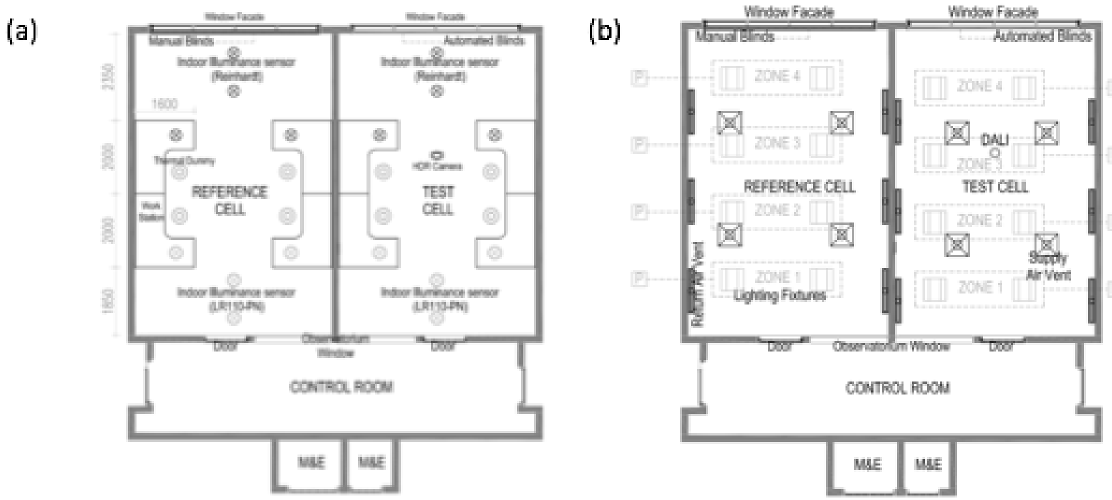

Figure 1: Experimental Setup. (a) Cell Arrangements; (b) Ceiling Installations

2.2 Lighting system

Each cell is fitted with 8 lighting fixtures. The lighting fixtures are mounted on the false celling at the height of 3.47 m from the finished floor. Each lighting fixture is 0.60 m long and 0.60 m wide. Two representative types of lighting are covered in this study: T5 fluorescent lamp and LED. The electrical power drawn by each lighting fixture is 51.75 W (T5) and 46.00 W (LED), at their respective maximum outputs. The lighting power density in the cell is 7.9 W/m^2 for T5 and 6.1 W/m^2 for LED.

Prior to the experiments, a lighting distribution test was carried out in both cells with all lighting fixtures set to maximum output. The test was conducted at night time with all windows blocked by papers to minimize external lighting disturbances. Illuminance measurements were made in a pre-defined grid of 1.07 m x 1.07 m per grid point covering the entire cell at the working plane height (height of work desk table top, 0.73 m above the floor) with a portable handheld lux-meter (Tenmars TM 202 Lux/FC). The test was conducted twice, once with T5 and once with LED. The average horizontal illuminance level at working plane height is 540.8 Lux with T5 lamps and is 538.9 Lux with LED. It is in compliance to the recommendation in SS531: Part1: 2006 (2013) of above 500 Lux at the working plane. The uniformities of illuminance in task area and surrounding area also conform to the recommendations in SS531: Part1: 2006 (2013) (task illuminance shall not be less than 0.7 and that of the immediate surrounding areas shall be not less than 0.5).

DALI dimming control (Lutron) was installed to provide auto dimming functionality to the lighting system. The DALI control system provides 4 settings: OFF, 25%, 100% and daylight responsive. The first 3 settings are manual overrides and the daylight responsive setting provides the auto dimming function. A daylight sensor is mounted on the ceiling 3.5 m away from window façade to detect the daylight conditions, providing the control feedback to the DALI system. The eight lighting fixtures in each cell are divided into 4 control zones as shown in Figure 1 (b). Zone 1 and zone 2 are individually controlled whereas zone 3 and zone 4 are controlled as one zone.

2.3 Blinds system

Conventional manual blinds, were installed inside of the reference cell. In the test cell automated daylight-redirecting blinds are installed. Both blinds systems are of Venetian type. The automated blinds were divided into two sections: the upper one-quarter-height portion consists of mirror-finish daylight-redirecting slats (50 mm wide, reflectivity: 0.91) and the lower three-quarter-height portion consists of mat-finish slats (25 mm wide, reflectivity: 0.56). The conventional manual blinds have the same mat-finish slats for full height. An in-house developed control algorithm was applied to control the automated blinds. The algorithm controls the lower portion such that the DGP of the person sitting at the work station closest to the wind façade will not exceed 0.35. The upper portion is controlled to allow maximum daylight penetration below the maximum threshold of 1,200 Lux of daylighting at the working plane. The manual blinds system is set at a predefined position (close/ open/ retracted) manually depending on experimental need.

2.4 Instrumentation

In each cell, horizontal illuminance at working plane height is measured by 8 illuminance sensors (4 further away from the window façade have a range of 0-10,000 lux (LR-110 PN), and the other 4 closer to the window façade have a range of 0-150,000 lux (Reinhardt)). One illuminance sensor (Reinhardt) is placed on the top of the roof to measure the outdoor horizontal illuminance at rooftop level. Glare in the test cell is measured using a High Dynamic Range (HDR) camera setup. Zonal lighting power is monitored by power meters (PowerLogic iEM3155). All sensors are reading and data-logging at 1-min intervals through the central DAQ of BCA SkyLab, apart from the HDR camera which used a 5-min interval due to the heavy processing power demand of imaging data. The sensor setup is shown in Figure 1 (b). Before the experiments, all the sensors and instrumentations have gone through systematic calibration and verification. The lux sensors have also been subjected to zero offsetting with their sensing elements closed using the factory-provided covers. Further, sensor signal noise is analysed by comparing the 2 × standard deviation of readings and noise-to-signal ratio with the documented accuracy of the sensors. The analysis ensures that the sensor signal noise does not exceed the documented accuracy range.

2.5 Experimental setup

Four tests were designed to study the performance of T5 vs LED, auto-dimming system, automated blinds system and the combined system. Each test runs from 9:00 am - 6:00 pm per day, following a typical office working schedule, for 3 days in May and Aug 2016. Table 1 summarizes the configurations of the four tests. Test 1 and Test 2 are conducted at blinds retracted condition to isolate the lighting energy savings potential of the auto-dimming system and the LED lighting. In Singapore, buildings are recommended to minimize façade exposure to the East and West orientations (Building and Construction Authority, 2010) and, thus, the North represents a typical façade orientation setting in Singapore. Test 3 and Test 4 study the integrated system consisting of auto-dimming lighting and automated blind. Test 4 has the same settings as Test 3 except that the façade orientation changes to East to investigate its impacts on energy savings potential of the integrated system.

Tests	Reference Cell	Test Cell	Façade Orientation
Test 1	Lighting: T5, Auto-dimming: No Blinds: Retracted	Lighting: T5, Auto-dimming: Yes Blinds: Retracted	North
Test 2	Lighting: T5, Auto-dimming: Yes Blinds: Retracted	Lighting: LED, Auto-dimming: Yes Blinds: Retracted	North
Test 3	Lighting: T5, Auto-dimming: No Blinds: Close	Lighting: LED, Auto-dimming: Yes Blinds: Automated	North
Test 4	Lighting: T5 Auto-dimming: No Blinds: Close	Lighting: LED, Auto-dimming: Yes Blinds: Automated	East

Table 1: Test cases

3. RESULTS

3.1 Auto-dimming lighting control

Table 2 summarises the lighting energy consumptions and energy savings achieved in the Test cell compared to the Reference cell. In Test 1, about 56.80% of lighting energy savings is achieved. Test 1 was conducted with both cells using T5 lighting fixtures and, thus, the energy savings obtained from this test reflects the energy savings due to auto-dimming.

	Lighting Energy Reference Cell(1)	Lighting Energy Test Cell (2)	Lighting Energy Savings (1) – (2)	Lighting Energy Savings [(1) – (2)]/(1) x100%
Test 1	9.90 kWh	4.28 kWh	5.62 kWh	56.80%
Test 2	3.52 kWh	2.06 kWh	1.46 kWh	41.52%
Test 3	9.79 kWh	2.51 kWh	7.28 kWh	74.35%
Test 4	9.87 kWh	3.66 kWh	6.21 kWh	62.92%

Table 2: Measured lighting energy consumption and savings

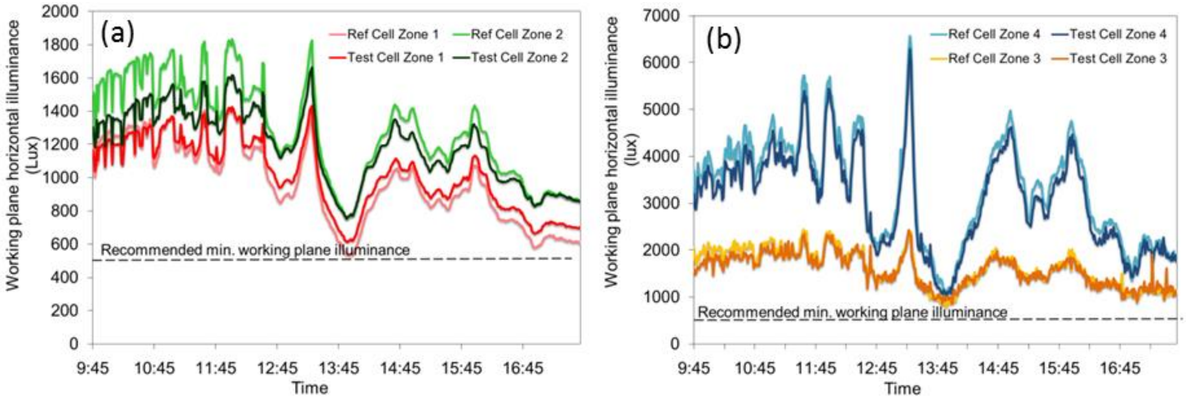

Figure 2: Working plane illuminance at each lighting zone for 1 day of Test 1

The horizontal illuminance at working plane in all lighting zones is maintained at over 500 lux during testing period, as depicted in Figure 2 (a) and Figure 2 (b). The high illuminance in zone 4 could be largely attributed to daylight penetration through windows.

3.2 T5 fluorescent lamp vs LED

Test 2 shows that about 42% of lighting energy savings is achieved by LED, compared to T5 lighting. Since this test is conducted with auto-dimming enabled in both cell, this saving by LED is achieved on top of the saving by auto-dimming. This could be due to the difference in dimming effects between LED and T5 as the two types of lamp has different lighting efficacy. The horizontal illuminance at the working plane is maintained at over 500 lux during testing period, in both cells.

3.3 Combined system

There is substantial lighting energy savings potential in an integrated system with auto-dimming lighting, automated blinds and LED. About 74% lighting energy savings was attained when the façade is facing North (Test 3). The working plane horizontal illuminance in both cells are maintained at above 500 lux as shown in Figure 3 (a) and Figure 3 (b), suggesting that the savings are obtained without compromising working plane illumination. The illuminance of zone 3 and zone 4 in test cell is higher than that in reference cell, indicating daylight penetration from automated blinds in test cell.

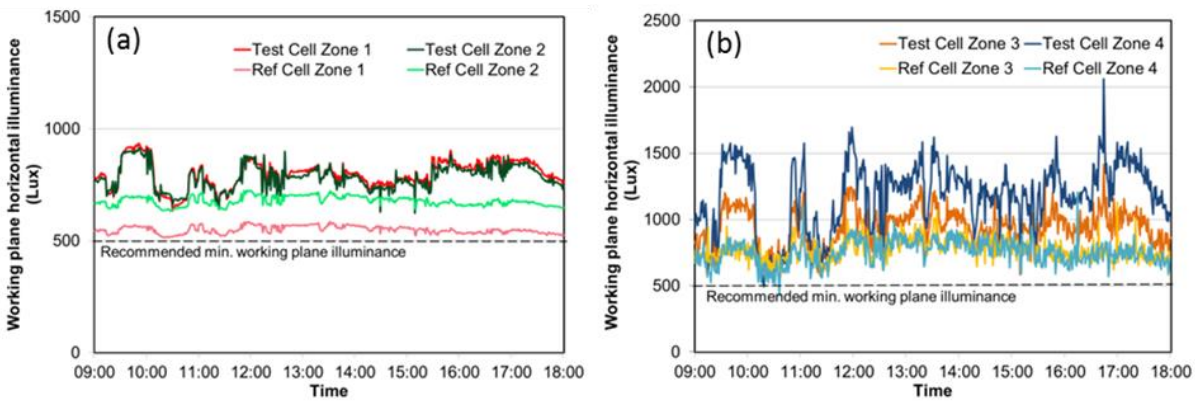

Figure 3: Working plane illuminance at each lighting zone for 1 day of test 3

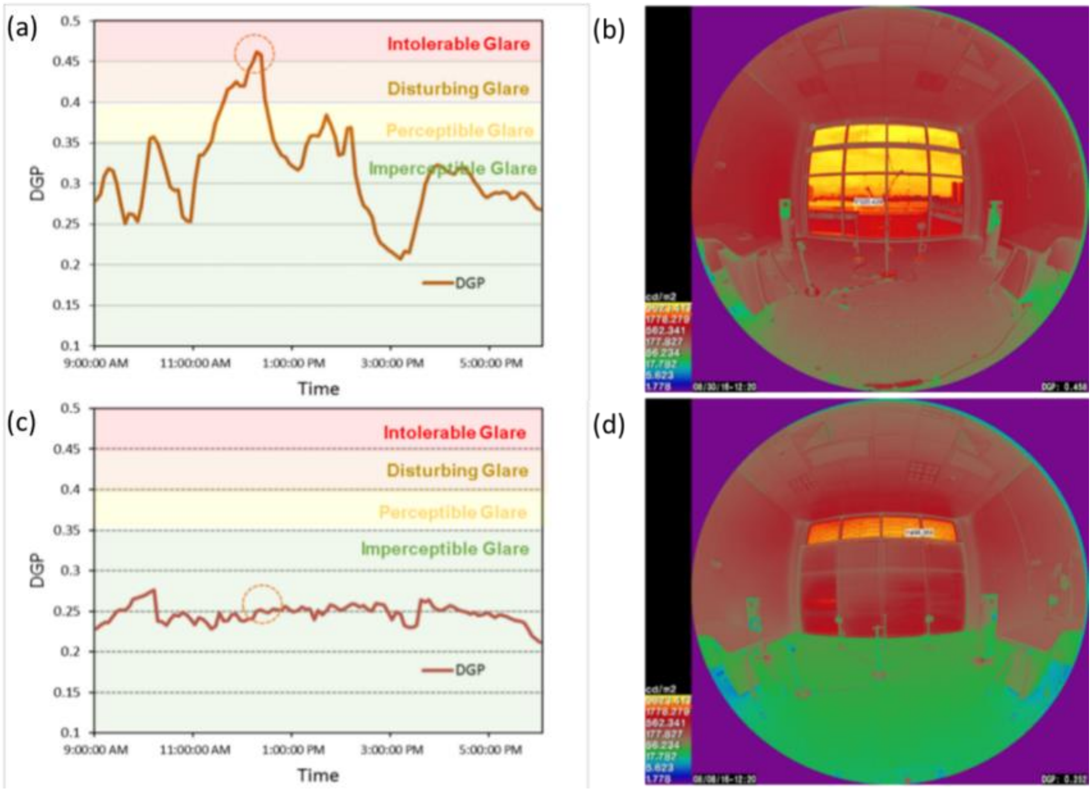

Figure 4: (a) DGP Profile of Test 1 (Blinds Retracted); (b) HDR Image at 12:20 pm during Test 1; (c) DGP Profile of Test 3 (Automated Blinds); (d) HDR Image at 12:20 pm during Test 3

While maintaining adequate horizontal illumination at the working plane (at above 500 lux), the integrated system maintains the Daylight Glare Probability (DGP) to be below 0.35 during the testing period, as shown in Figure 4 (c). It indicates that the automated blinds have successfully controlled glare according to the glare level classification in Jakubiec & Reinhart (2012). The DGP profile of Test 1 (blinds retracted) is shown in Figure 4 (a) for comparison. In Test 1, DGP exceeds 0.35 (threshold for perceptible glare) at certain time of the day and reaches a maximum of 0.46 (intolerable glare) at 12:20 pm. DGP at the same time of the day in Test 3 is 0.24.

The impact of facade orientation is examined by running the same test but with façade orientation adjusted to facing East (Test 4). The Test cell consumes significantly more lighting energy in Test 4 compared to Test 3 (see Table 2), suggesting that the East façade orientation has less daylight availability (and potential for dimming) than the North orientation. This could be due to the fact that although there is ample amount of daylight available in the morning in the East orientation, the East-facing façade is under the shadow of the lab itself in the afternoon and, thus, less daylighting potential compared to North on a daily basis. This is reflected in the system's ability to save lighting energy consumption. The same integrated system saves only about 63% of lighting energy in Test 4, lesser than the 74% in Test 3. However, the integrated system is still able to maintain the DGP at below 0.35 and working plane horizontal illuminance at above 500 lux during daytime in Test 4. Visual comfort is not compromised in both orientations.

4. DISCUSSION

Current results suggest that more lighting energy savings can be achieved if more daylighting is available. This matches with the observations in some previous studies, e.g., Lee et al. (1998), Lee et al. (2009), Chaiwiwatworakul et al. (2009), etc. Taking weather conditions, building orientation and sky view condition into account in evaluating the performance of auto-dimming and automated blinds is important. This paper provides the first report on the performance of an integrated lighting and daylighting control system in a rotatable testbed in tropical region.

An outdoor rotatable test facility with plug-and-play capability provides a highly flexible test bed for various green building technologies. The BCA SkyLab allows the test bedding of individual technology or a number of technologies simultaneously as an integrated system, leading to new scientific insights on the performance and characteristics of green building technologies.

5. CONCLUSION

This study investigates the lighting energy performance and visual comfort of several lighting and daylighting technologies: LED, auto-dimming lighting and automated blinds in a rotatable test facility, BCA SkyLab, in Singapore. The interior of the facility simulates a typical office environment. Compared to non-dimmable lighting, auto-dimming lighting shows about 57% savings in lighting energy consumption. LED lamps provide about 42% of lighting energy savings compared to T5 fluorescent lamps. An integrated system consisting of LED lamps, auto-dimming lighting control and automated blinds achieves up to 74% of lighting energy savings compared to a base system consisting of T5 lamps, non-dimmable lighting control and manual blinds. The energy savings potential increases with daylight availability. In Singapore's tropical climate, the integrated system shows excellent capability to provide visual comfort while achieving significant lighting energy savings, demonstrating the value of an outdoor rotatable test facility in R&D.

Future work can include evaluating thermal performance of the integrated system, testing its performance in other building orientations with longer durations, as well as further integration with air-conditioning control to optimise the energy performance of the system.

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