

## Accepted Manuscript

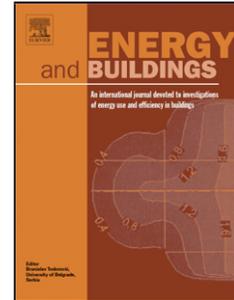
Title: Daylighting and solar shading performances of an innovative automated reflective louver system

Author: Arman Hashemi

PII: S0378-7788(14)00635-5  
DOI: <http://dx.doi.org/doi:10.1016/j.enbuild.2014.07.086>  
Reference: ENB 5238

To appear in: *ENB*

Received date: 27-12-2013  
Revised date: 1-4-2014  
Accepted date: 30-7-2014



Please cite this article as: A. Hashemi, Daylighting and solar shading performances of an innovative automated reflective louver system., *Energy and Buildings* (2014), <http://dx.doi.org/10.1016/j.enbuild.2014.07.086>

This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

**Title:**

Daylighting and solar shading performances of an innovative automated reflective louver system.

**Author name and affiliations:**

Dr Arman Hashemi

- 1- The Bartlett School of Architecture, University College London, London, WC1H 0QB, UK.
- 2- SE Controls, Lichfield, Staffordshire, WS13 8RZ, UK.

**Current/corresponding address:**

Centre for Sustainable Development  
Grenfell-Baines School of Architecture, Construction and Environment  
University of Central Lancashire  
Preston, PR1 2HE, UK.

Tel: +44 (0) 1772894209

Fax: +44 (0) 1772892916

Email: [ahashemi@uclan.ac.uk](mailto:ahashemi@uclan.ac.uk)

**Title:**

Daylighting and solar shading performances of an innovative automated reflective louver system.

**Abstract**

Traditional windows, as the major source of daylight, have a common problem which is uneven distribution of daylight in the room. Several innovative daylighting systems such as light shelves, fixed and movable reflective louvers, reflective sills, prismatic glazing, light pipes etc. have been developed to address this problem. This paper reports on a research programme that investigates retrofitted solutions to uneven distribution of daylight in deep-plan office buildings. The work presented here follows initial investigations into the design and applicability of an automated retrofitted panel thermal shutters which can also act as a sunshade and daylighting system. The system has a patented function which allows each shutter/louver to be controlled and placed separately from other louvers. This study evaluates the effectiveness of the system when acting as a sunshade, light shelf, reflective louver, and reflective sill under clear, overcast, and sunny sky conditions. According to the results, the system significantly improved daylight distribution and reduced the need for artificial lighting by 60%.

**Keywords**

Reflective louver, light shelf, reflective sill, solar shading, daylight, retrofit, energy efficiency.

**Nomenclature:**

**Average Daylight Factor (ADF):** is the “ratio of total daylight flux incident on a reference area to total area of reference area, expressed as a percentage of outdoor illuminance on a horizontal plane due to an unobstructed hemisphere of sky of assumed or known luminance distribution” [1]. ADF can be calculated using the following equation [2]:

$$ADF = TA_w \theta M / \{A(1 - R^2)\}$$

T: the glass transmittance;  $A_w$ : the effective window area (excluding the frames);  $\theta$ : the visible sky angle; R: the average reflectance of the room, M: the maintenance factor; A: the total surface area of the room in  $m^2$  (floor + ceiling + walls including the windows).

**Limiting depth of the room (L):** the maximum room depth which is sufficiently daylit in a room with windows on one wall only. L is calculated from the following equation [2]:

$$L/W + L/H_w < 2/(1 - R_b)$$

W: room width; H: window head height above floor level;  $R_b$ : the average reflectance of surfaces in the back of the room.

## 1 Introduction

The UK's government has long-term objectives to reduce carbon emissions by 80% by 2050 [3,4]. The construction industry is one of the major sectors which should contribute towards achieving these objectives. The construction industry is accounted for 47% of the CO<sub>2</sub> emission of the UK, 80% of which is generated from the "In-Use" buildings [5]. The government has announced its ambition to make new homes and non-domestic buildings carbon neutral in order by 2016 and 2019 [6,7].

Although important, such policies do not address the existing commercial buildings. With an annual replacement rate of 1-1.5%, it is estimated that, by 2050, around 70% of the existing buildings will still be in use, 40% of which have been built before 1985 [4]. Therefore, to achieve such challenging targets, it is vital to improve the energy performance of the existing commercial buildings.

One of the major areas of improvement is the effective use of natural lighting. Lighting accounts for around 5% of the total energy consumption in the UK and 10-30% of the energy consumption in buildings such as offices [2]. Between 20% to 60% saving in lighting is achievable by improved use of daylight [8,9]. Appropriate lighting controls are however required to achieve such savings [2,10].

There are no legal requirements for daylight levels in the UK [2]; however, according to the Workplace (Health, Safety and Welfare) Regulations, "Every workplace shall have suitable and sufficient lighting" and the lighting "shall, so far as is reasonably practicable, be by natural light." Moreover, "Dazzling lights and annoying glare should be avoided" [11]. Building regulations also do not specify the minimum requirements for daylighting; however, according to Part L of the Building Regulations, glazing area should not be much less than 20% of the total floor area as this may result in poor natural lighting and increased use of artificial lighting [12].

Meanwhile, increasing pressure on building designers and owners to improve the thermal performance of their buildings has resulted in the reduction of the total window areas and replacement of single glazed windows with double and triple glazed Low-E units. Although such systems improve the thermal performance of the building, they considerably reduce the transmitted visible light from the exterior to the interior. Typically "Low E" systems transmit 50% of the light compared to 70% transmission through double glazed units and 90% transmission through single glazing [10].

Daylight quality and distribution depends not only on the glazing type and area, but also on several other factors including sky conditions, time, building locations, window proportions and orientations. Daylight is not therefore a reliable source of lighting as its colour and intensity changes constantly [13,14]. For this reason, a combination of daylight and electric lighting is required in the buildings.

Average Daylight Factor (ADF) is a concept which is commonly used in early stages of design to estimate the required window area in order to achieve adequate daylight in a building [15,16]. In simple terms,

$ADF = \frac{E_i}{E_o} \times 100\%$ , where  $E_i$  is the average internal and  $E_o$  is the external illuminance [17,18]. According to

BS 6262-2:2005 and BS 8206-2:2008 if ADF is at least 5% and daylight distribution is satisfactory, artificial

lighting is not normally required; and, if ADF is between 2% and 5% supplementary artificial lighting is usually required. If ADF drops below 2% electric lighting is almost always required [2,16,19,20].

The use of electric lighting not only depends on the ADF but also on the even distribution of daylight. Increasing ADF will not be effective on its own if daylight distribution in the building is poor [10]. In this respect, an area with a 2% daylight factor and a uniformity of 40% will look more attractive than a space with a daylight factor of 5% and a uniformity level of 10% [21]. A uniformity level of 30-50% [21] is recommended to maximise benefiting from natural lighting.

Traditional windows, as the major source of daylight, have a common problem which is uneven distribution of daylight in the room [13]. For this reason, if a room is daylit by windows in only one wall, the depth of the room should be limited to the “limiting depth of the room” to receive sufficient daylight. However, this is not always possible and therefore several innovative daylighting systems such as light shelves, fixed and movable reflective louvers, reflective sills, prismatic glazing, light pipes etc. have been developed to address this problem. These systems have been explained and tested in several documents [8,10,13,22-33].

Daylighting systems improve natural light distribution and reduce the excessive contrast and use of electric lighting in buildings [10,13,22]. Many of these systems work optimally under sunny conditions [13,31] and may cover one or some of the following functions [23]:

- solar shading
- glare protection; and
- daylight balancing

Each of these systems, however, has its own problems and limitations. For instance, light shelves do not in general increase the light in deeper areas in the room [34] and they may require additional devices, such as blinds, to control sunlight and glare [10]. Fixed louvers may considerably reduce the interior light [10,20,22,23]; and, automated systems may cause distraction [10,34].

It is in this context that the author reports on a research programme that investigates retrofitted solutions to this problem. The work presented below follows initial investigations into the design and applicability of an automated retrofitted panel thermal shutters as a collaborative work between University College London and SE Controls. The system has a patented pick & place function [35] which allows each shutter/louver to be controlled and placed separately from other louvers. This function makes the system extremely flexible resolving some of the abovementioned problems of daylighting systems. This study intends to evaluate the effectiveness of the system when acting as a sunshade and light reflector (in three different modes of reflective louver, light shelf, and reflective sill) under clear and overcast sky conditions. The thermal performances of the system have been investigated and discussed in another paper [36].

## 2 Methodology and equipment

The methodology of this study is to directly compare the results of computer simulations, physical tests carried out on a one to one scaled model, and parallel measurements taken in an office located in the case study building. The focus of this study is mainly on the relative and not absolute daylight measurements.

All physical tests were carried out for a minimum of three days under similar sky conditions and averages were taken to minimise inaccuracies [23]. Also considering dynamic nature of the sky conditions, measurements were taken every minute to increase the accuracy of the results.

HOBO U12/12 data loggers were used for internal and HOBO Pendant for external daylight measurements. According to the manufacturer's technical datasheets, the sensors are appropriate for relative daylight measurements. A handheld meter (Precision Gold NO9AQ) was also used for the absolute daylight measurements. The instrument is fully cosine corrected for the angular incidence of light. Pilot studies revealed considerable deviations in the readings by the HOBO data loggers. All sensors were therefore calibrated prior to starting the tests. Yet, 5% and 10% reading tolerances should be considered for the internal and external sensors respectively.

## 3 Case study building and surrounding environment

The physical tests took place at SE Controls located in Fradley Park, Lichfield, UK. The building is situated on a business park and is oriented 68 degrees east of due south with some external natural obstructions. The test rooms were situated on the ground floor and the office was located on the first floor of the building. Figure 1 shows the building orientation, the position of the test windows and the sun path on the 22<sup>nd</sup> of June, March and December.

### Position of Figure 1

As shown in the panoramic view (Figure 2), apart from some distant rows of trees, the space in front of the tested building was almost free from obstructions; however, some leafless trees and bushes (around 1800mm tall and 6m away from the windows) were blocking some of the sky.

### Position of Figure 2

### 3.1 Test rooms and measurement processes

The test and reference rooms were created by dividing a four meter window into two equal parts. Blackout off-white curtains were used to stop the light from getting inside or outside the rooms. Electric lights and heaters were also switched off for the duration of the test. The rooms were mirrored in terms of the position of the curtains and window openings with some minor differences in the position of the ceiling lights. The ceiling was made out of white ceiling tiles and the floor was covered with dark blue carpet. Figure 3 and Figure 4 show the position of the equipment in the test and the reference rooms.

### Position of Figure 3 & 4

Interior illuminance was measured for the work plane at 0.85m above the floor using HOBO U12/12 data loggers. The data loggers were equally spaced and positioned at, in order, 0.6m, 1.8m, 3m and 4.2m from the window. Four external data loggers (two attached to the building façade and two placed on the roof facing the sky with an almost unobstructed horizon) were also positioned outside to measure and record the vertical (combined ground and sky) and horizontal global illuminance. Two cameras (Cam 1 and Cam 2) were also positioned at 1.2m (eye level of a seated person) 4.8m away from the window to take still images of the rooms every minute. Cam 3 also constantly monitored and recorded the sky conditions. In addition, sky conditions were manually recorded every half an hour.

Moreover, two sensors were attached to Cam 1 and Cam 2 to measure the vertical illuminance at the back of the room. Sensors 6 and 7 also recorded the transmitted light through the windows. All internal sensors were set to record the temperature as well as the illuminance.

Reactions of people in different times of the day to different sky conditions, positions of blinds, and the use of electric lights were also monitored and recorded manually in an office located directly above the test and reference rooms.

A 1:1 adjustable mock-up of the louver system was built and fixed in the test room to evaluate the performance of the reflective louver system. The reflective louvers were made from 18mm softwood timber board one face of which was covered with highly reflective aluminium tapes (Figure 5).

### Position of Figure 5

## 4 Computer simulations

Hundreds of computer simulations were conducted in IES (VE) to investigate the most effective louver configurations with regards to daylight distribution and blocking the sunlight to avoid glare (for sunny conditions, while allowing maximum daylight in). The results of the simulations were the basis of the physical tests explained in the following sections.

A 2.2x5m room with a 2m window and a suspended ceiling at 2.3m above the floor was modelled to reflect the actual conditions of the test and reference rooms. The sill and head heights of the window were in order 900mm and 2100mm above the finished floor level. The simulations were conducted for the following configurations on the Equinox (21<sup>st</sup> of March) for the clear and CIE standard overcast sky conditions and for the 300x20mm reflective louvers:

- Equally spaced louvers at 0°, +/-15°, -30°, and -45° degrees (tilted towards inside)

- Horizontal and +/-15°, -30°, and -45° degrees tilted light-shelf (one louver at 1800mm above the finished floor and the rest stacked at the bottom of the window)
- Louvers stacked at the bottom of the window (reflective sill)
- Bare window

Birmingham Airport, UK was considered as the location of case study building for the purpose of the simulations.

#### 4.1.1 Results of simulations

The results of IES simulations showed that the Average Daylight Factor in the room decreased for all louver configurations regardless of the louvers' positions and sky conditions. However, the system enhanced the light distribution and decreased the contrast between the areas closer to the window and areas deeper in the room.

The simulations also showed that equally spaced horizontal and -15 degrees tilted (towards inside) louvers noticeably enhanced the light distribution for both clear and overcast sky conditions; however, tilted louvers provided higher daylight levels at the back of the room. The results also revealed that, although -15 degrees tilted light-shelf worked slightly better than the horizontal one in terms of daylight redistribution, it was not as effective as the equally spaced louvers particularly under overcast sky conditions. The light redirection/distribution properties of the system deteriorated for -30 and -45 degrees tilted louvers. Figure 6, 7, 8 and 9 show the results of the computer simulations for different louver configurations which enhanced daylight distribution on the work plane at 0.85m above the floor.

#### Position of Figure 6, 7, 8 and 9

Several simulations were also conducted in IES Radiance for sunny sky conditions from 9am to 1:00pm during which the sun would fall on the actual tested windows. This was to study the effectiveness of the system to act as a sunshade and to identify the minimum louver angles (with 5-degree steps) at which the sunlight was blocked while maximum daylight was let in. The simulations were conducted for the 26<sup>th</sup> of March (expected start date of the physical tests) every half an hour for equally spaced louvers. Table 1 summarises the results.

#### Position of Table 1

## 5 Physical tests

Physical tests were carried out in the case study building for several months in order to achieve a target minimum of three days of similar sky conditions for averaging purposes. The results of the physical tests are explained below.

## 5.1 Results of physical tests

As mentioned above, the system was principally tested in two main configurations of sunshade and light-reflector. In sunny conditions, when direct sunlight fell on the windows (from 9am to 1pm), the system acted as both sunshade and light reflector; and, for all other conditions (overcast sky and after 1pm) it acted as a light reflector only. Figure 10 shows the louvers in light shelf and sunshade modes under cloudy and sunny sky conditions.

### Position of Figure 10

#### 5.1.1 Sunny/Clear sky conditions

Figure 11 shows the results of the tests under sunny and clear (without direct sunlight) sky conditions. Sensors A, B, C, D and E placed in the test room correspond to sensors 1, 2, 3, 4 and 5 which were positioned in the reference room. The louvers were manually adjusted every half an hour to block the sun from 9am to 1pm according to the results of IES Radiance simulations explained above. After 1pm, when direct sunlight was not falling on the windows, the system was tested in various arrangements including stacked/retracted (reflective sill), horizontal and -15 degrees tilted light-shelf (LS).

### Position of Figure 11

According to the results, during morning, although the ADF reduced from around 7% to 1.5%, the system considerably decreased the contrast and risk of glare in the test room. The results show that, in the worst case scenario, the light intensity in the reference room has been around 18000lux for Sensor 1 (in the sun) and 300lux for Sensor 4 which means a ratio of 1:60. The light intensity in the test room in the worst case scenario has been around 4000lux for Sensor A and 270lux for Sensor D meaning a ratio of 1:14.

The results show that the most effective arrangement has been the 5 degrees tilted louvers (11:30am-12pm) which has increased the light by an average of 19.5% in the middle of the test room compared to the reference room. During afternoon, none of the arrangements improved the situation and in fact they decreased the available light by an average of 6% in the second half of the test room.

Figure 12 shows a comparison between the vertical illuminance at the back of the test and reference rooms. The results show that the system has, in all cases, reduced the vertical illuminance at the back of the room. The ratio between the vertical luminance in the reference to the test room has decreased from an average of 2.8 in the morning to 1.1 in the late afternoon.

### Position of Figure 12

The results also indicate that the system has been rather effective in controlling solar heat gains during morning when it acted as a sunshade. Although the only barrier between the test and reference rooms has been the curtains, there has been a considerable temperature difference of around 1.5C° between the test and the reference rooms in early hours of the morning for the areas outside the sun. The temperature difference was obviously much higher (around 7C°) for the areas in the sun. The temperature difference would

gradually decrease until they matched. Figure 13 shows the delayed rise of temperature in the test room under sunny sky conditions for two days with similar sky condition.

#### Position of Figure 13

### 5.1.2 Overcast sky

For the overcast sky conditions, based on the results of IES simulations explained above, the reflective louver system was tested in three different configurations as follows:

- -15 degrees tilted light-shelf
- -15 degree equally spaced louvers
- Horizontal equally spaced louvers

Figure 14 shows the results of the tests for the -15 degree tilted light-shelf.

#### Position of Figure 14

According to the results, the system has slightly improved the available light in the second half of the test room. The available light has almost remained unchanged for areas closer to the window and improved by an average of 12% at the back of the test room.

The results show that the system has been rather effective and has almost doubled the available light at the second half of the room when the horizontal illuminance for Sensor 1 dropped below 200lux. However, for such dull weather conditions, electric lights were required regardless of the system effectiveness. The 12% average improvement, mentioned above, dropped to an average of 7% when the extreme conditions were removed from the data.

Comparison between the vertical illuminance at the back of the test and reference rooms (Figure 15) reveals that the system has reduced the vertical illuminance by around 7% at the back of the room regardless of the external light levels.

#### Position of Figure 15

According to IES simulations, equally spaced tilted louvers were considerably effective in terms of daylight distribution; however, this arrangement noticeably reduced the light levels for areas close to the window. This was also confirmed by the physical tests (Figure 16). The results revealed that although daylight levels were reduced by an average of 48% in areas close to the window, it increased by an average of 63% at the back of the room. The 63% increase dropped to an average of 47% when the extreme conditions (under 20lux for Sensor D) were removed from the data. The improvement in the daylight distribution was clearly evident when comparing the test and reference rooms with naked eyes at different times of the day.

Moreover, the vertical illuminance increased by an average of 25% and the average contrast between front and the back of the room decreased to around one third. The latter is particularly important in reducing the glare and use of artificial lighting [21].

#### Position of Figure 16

Equally spaced horizontal louvers were not as effective as the tilted louvers (Figure 17). In fact this configuration deteriorated the situation by reducing daylight factor by an average of 64% (from 4.1% to 1.5%) for the areas close to the window and keeping it almost unchanged for the rest of the room. One explanation for this may be that the reflected light by the louvers was actually blocked by the next louver above stopping the system to optimally act as a light reflector.

#### Position of Figure 17

## 6 Occupants' behaviours and natural lighting

In addition to the computer simulations and physical tests, some parallel measurements were taken in an open plan office located directly above the test rooms. This was particularly important to compare the results with the actual conditions in the real world.

The reactions of occupants to different sky conditions, positions of vertical blinds and use of electric lights in the office were continuously monitored and recorded manually. The available daylight levels on the working plane in different parts of the office and the rooms were also recorded with a handheld light meter.

### 6.1.1 Results of the observations

The observations showed that people (who were sitting next to the windows) had different attitudes and reactions towards the sunlight as some would completely block the sun by closing the blinds and others were more tolerant allowing some sun rays into the building. However, the blinds were never fully open in sunny conditions. Such different attitudes had a great influence on the available daylight at the back of the room and the need for artificial lighting.

According to the results of the physical experiments, during early morning, when steeper louver angles (e.g. 45 degree) were required to block the low level sun, available daylight in the test room was considerably lower than in the reference room. This said, compared with the above offices, available daylight was considerably better particularly for deeper areas in the room. This was because during sunny mornings occupants would almost completely shut the blinds to avoid direct sunlight and glare. This, in almost all cases, would result in switching the electric lights on as the office would look extremely dark particularly for people seating away from the windows.

Table 2 shows a comparison between the available daylight on the working plane at 0.85m above the floor in the office and the test room for three days between 9:00am and 9:30am under sunny conditions.

### Position of Table 2

According to the results, in the best conditions, available daylight in the office has been around 8 times less than in the test room. In the worst case scenario, available daylight in the office has been around 43 times less than in the test room. The electric lights were therefore switched on particularly for people sitting away from the windows.

The observations also revealed that people's reaction to direct sunlight and glare was almost immediate as they would almost immediately close the blinds to avoid glare; however, they did not react as quickly when the sky conditions changed to, for example, cloudy. Therefore, the blinds remained closed and electric lights remained on despite the fact that adjusting the blinds would have removed the need for artificial lighting. Even after delayed reactions, when people opened the blinds, electric lights remained on, in almost all cases, for the rest of the day.

Other studies mention this as a potential issue in offices with manually controlled blinds [10,22,29,34,37]. According to Littlefair (1996), in offices with manual light switches, depending on the available daylight at the beginning of the day, people switch the lights on and leave them on for the rest of the day [22]. Some studies however indicate that occupancy patterns and staff habitual actions are the key reasons for switching the lights on rather than the external illuminance [38]. Regardless of the reasons, this situation can result in considerable energy waste in buildings with manually controlled blinds and lights. An automated system combined with automatic light switches could resolve this issue.

## 7 Discussions

This section intends to evaluate the potential savings in electric lighting when the reflective louver system acts optimally under overcast, sunny and clear sky conditions. The tested system proved to be very effective as it considerably decreased the contrast throughout the test room and increased the available daylight in deeper areas of the room by an average of 47% and 19.5% under overcast and sunny sky conditions respectively. However, these figures do not represent the potential savings in electric lighting.

The tested windows were double pane tinted glass in an aluminium glazing system. The initial tests on the windows under overcast sky conditions revealed that they decreased the transmitted light to just under a third (32.8%) compared to a typical double glazed unit which transmits around 70% of the light [10]. According to CIBSE, depending on the sky condition, light transmissions under 32-38% is usually regarded as unsatisfactory and tinted windows are not recommended for daylighting systems and should be avoided if possible[10]. A correction factor of 2.13 ( $70/32.8 = 2.13$ ) was therefore applied to the light intensity readings to evaluate the overall energy saving performances of the system for a typical double glazed window.

According to SLL Lighting Handbook published by CIBSE, the recommended maintained illuminance in "Open plan office – mainly screen based work" is 300lux [34]. The following results are concluded assuming that a light dimmer system is installed in the case study building to maintain the light intensity [39] to a minimum of

300lux throughout the office. It is also assumed that there is a linear relationship between energy consumptions and light levels [40]. For the purpose of the evaluations, the office was divided into four zones of:

- Zone 1: 0.6m away from the window (Sensors 1 and A)
- Zone 2: 1.8m away from the window (Sensors 2 and B)
- Zone 3: 3m away from the window (Sensors 3 and C); and
- Zone 4: 4.2m away from the window (Sensors 4 and D)

Similar to actual conditions of the case study building, one set of fluorescent lights was considered for Zones 1&2 and another set for Zone 3&4.

According to the results of both physical tests and computer simulations, -15-degree equally spaced louver was the optimum louver arrangement for the system under overcast sky conditions. For this arrangement the louver system maintained the minimum 300lux requirement in Zone 1 however it increased lighting requirement by around 5.6% in Zone 2. The electric lighting requirements reduced by around 5% and 8.6% in Zone 3 and Zone 4 of the office respectively (Table 3). Therefore, it could be argued that the system reduced the electric lighting requirements by an average of 8% in total.

#### **Position of Table 3**

For sunny conditions, similar to the reference room with bare windows, the system provided the minimum 300lux requirement for all zones during the morning (Table 4) meaning a 0% saving in electric lighting. However, considerable savings are achievable when results are compared with the real conditions in offices with manually controlled blinds.

#### **Position of Table 4**

According to the results of the observations explained above, during sunny conditions, occupants adjusted the blinds to avoid glare. This in turn resulted in great variations in available daylight particularly at the back of the office. As during sunny mornings, blinds were almost in all cases closed until 1pm, electric lights were required in the second half of the room. Results of the observations and measurements revealed that the average available lights for areas close to and far from the windows were 494lux and 57lux respectively. Therefore, electric lighting was required for the second half of the room to maintain the minimum 300lux requirement. This is while the reflective louver system in sunshade mode provided the required 300lux in 97% of the times for all zones meaning an average saving of 40.5% compared with manually controlled blinds.

Meanwhile, considering the existing controls for electric lights in the case study building (where all lights for different zones were controlled together), electric lights were switched on even for the Zone 1&2 which were receiving enough daylight. This situation resulted in 50% more energy waste in sunny conditions. Therefore, a

maximum saving of 90.5% ( $40.5\%+50\%=90.5\%$ ) in electric lighting is achievable if the automated reflective louver system and electric lighting controls are installed in the office. Similar conditions apply when the system acts as a reflective louver under overcast sky conditions meaning a saving of up to 58% ( $8\%+50\%=58\%$ ) when compared with manually controlled blinds and light switches (Table 5). It is obvious that even more savings are achievable considering the occupants' behaviours which may leave the lights on for the entire day regardless of sky conditions and available daylight levels in different times of the day [10,22,29,34,37].

For the clear sky (with no direct sunlight on the windows), as indicated by the results of the physical tests, due to the adverse performance of the system, the louver system is assumed to be kept retracted which means 0% saving in electric lighting while allowing the maximum view out. Table 5 summarises the possible savings in electric lighting for different conditions with and without reflective louver system in the case study building.

#### Position of Table 5

The overall potential savings were also calculated for the duration of the study (11weeks). According to the observations and recorded daylight levels by data loggers, there were 78 hours of sunny conditions during mornings (when the system should act as a sunshade) representing 18.2% of the total testing period excluding weekends. There was also 28 hours of clear sky conditions during afternoons (6.5% of total testing period) leaving 75.3% cloudy conditions when the system should act as a reflective louver. Therefore, it could be argued that around 60% ( $[(18.2 \times 90.5)+(6.5 \times 0)+(75.3 \times 58)]\%=60.14\%$ ) saving in electric lighting could have been achieved if the reflective louver system and lighting controls were installed in the office during this period.

## 8 Conclusions

Auxiliary sidelighting systems such as light-shelves and reflective louvers, in general, reduced the average daylight in the room [10,20,23,34]; however, they potentially decrease the need for artificial lighting by improving daylight distribution in the building [10,13,22].

Similar to other daylighting systems, the tested device worked optimally under sunny conditions by decreasing the contrast between the areas close to and far from the windows. Unlike some systems (e.g. fixed light-shelves) which may cause low daylight levels under overcast sky conditions [41], the tested system proved to be effective under overcast sky conditions as it significantly improved the available light at the back of the room by an average of 47% when acting as reflective louver; however, it was not as effective under clear sky conditions.

The effectiveness of automated daylighting systems in buildings becomes more evident when their performance is compared with traditional manually controlled shading devices such as venetian blinds. Automated systems can eliminate the extreme conditions and remove the delayed reaction of occupants to sky conditions providing a much more robust and balanced daylight levels in the building. It should be born in

mind that daylighting systems should be used in conjunction with electric lighting controls to achieve their optimum performance [2,10]. Only then they can reduce the use of artificial lighting in buildings.

The tested system, offered an average saving of 60% in electric lighting when it was used in conjunction with electric light controls. The performance of daylighting systems, however, depends on several issues including the occupants' behaviours, electric light zoning, window properties and orientations, building locations, and climatic conditions of the country where they are used. Computer simulations and/or physical measurements are therefore required for accurate evaluation of such systems in different conditions.

The benefit of some daylighting systems go beyond their light distribution properties. Similar to reflective internal solar blinds [13,42], the tested system delayed the air temperature rise by blocking/reflecting the sunlight which is considered as one of the most important factors in overheating in buildings [2,29,34,43,44]. Delayed temperature rise in addition to high daylight efficiency are particularly important when considering natural and mechanical ventilations strategies to reduce the cooling loads. Such potential benefits of daylighting systems need to be explored in more detail.

As a general issue, reflective louver systems may block the outside view by covering a large portion of the windows. Moreover, although automated systems have a better daylighting performance [25], they may cause distractions [10,34]. Careful design should therefore be considered to minimise such negative effects. In addition, many auxiliary daylighting systems should be integrated in the design stage of the buildings in order to achieve their best performance [13]. The tested device, however, proved to be an effective retrofitted product which can considerably reduce the need for artificial lighting in buildings.

This research investigated the effectiveness of an innovative automated daylighting system when acting as a sunshade, light shelf, reflective louver, and reflective sill. Further research is required on the following subjects:

- An appropriate control strategy should be developed for the system not only to maximise daylight distribution but also to minimise the operation frequency (to minimise distraction and energy consumption) by finding optimum configurations in response to internal and external conditions.
- The overall energy performance of the system (combination of thermal, daylighting, and solar shading) should also be studied in more detail.
- This study was not in general concerned about the possible secondary glare caused by the system when acting as a light reflector. More research is required in this respect.

## 9 Acknowledgments

The author of this paper would like to thank SE Controls and the Bartlett School of Architecture, University College London, for their supports, encouragements, and valuable contributions throughout the development and testing processes of this product.

## 10 References

- [1] BSI, BS 6100-7:2008, 59012: Building and civil engineering – Vocabulary – Part 7: Services, British Standard Institute, London, 2008.
- [2] BSI, BS 8206-2:2008: Lighting for buildings, Part 2: Code of practice for daylighting, British Standard Institute. Second edition, London, 2008.
- [3] Legislation.gov.uk, Climate Change Act 2008, online: <http://31.legislation.gov.uk/ukpga/2008/27/contents> (Accessed: 26/11/2013)
- [4] J. Rhoads, Low Carbon Retrofit Toolkit: A roadmap to success, Better Buildings Partnership, London, 2010.
- [5] BIS, Estimating the amount of CO2 emissions that the construction industry can influence, Department for Business, Innovation and Skills, London, 2010.
- [6] Communities and Local Government, Definition of zero carbon homes and non-domestic buildings, Department for Communities and Local Government, London, 2008.
- [7] UK-GBC, Building Zero Carbon – the case for action, UK Green Building Council, London, 2014.
- [8] V.H.C. Crisp, P.J. Littlefair, I. Cooper, G. McKennan, Daylighting as a passive solar energy option an assessment of its potential in non-domestic buildings. Building Research Establishment, Watford, 1988.
- [9] P. Littlefair, A. Slater, M. Perry, H. Graves, D. Jaunzens, Office lighting, BRE Environmental Engineering Centre, Watford, 2001.
- [10] CIBSE, Lighting Guide LG10: Daylighting and window design, The Chartered Institution of Building Services Engineers, London, 1999.
- [11] HES, Workplace (Health, Safety and Welfare) Regulations 1992 Approved Code of Practice, Twelfth edition, HSE, London, 2004.
- [12] HM Government, The Building Regulations 2000: Approved Document L1A: Conservation of fuel and power in new dwellings, NBS, London, 2010.
- [13] M. Bubekri, Daylighting, Architecture and Health: Building Design Strategies (1st ed.) Architectural Press, Oxford, 2008.
- [14] BRE, Estimating daylight in buildings: Part 1, An aid to energy efficiency, Building Research Establishment, Watford, 1986.
- [15] J. Bell, W. Burt, Designing buildings for daylight, Construction Research Communication Ltd, Watford, 1995.

- [16] BRE, Desktop guide to daylighting - for architects, Good Practice Guide 245, Building Research Establishment, Watford, 1998.
- [17] P. J. Littlefair, Site layout planning for daylight and sunlight: A guide to good practice, (2nd ed.), Building Research Establishment, Watford, 2011.
- [18] S.V. Szokolay, Introduction to Architectural Science: The Basis of Sustainable Design (2nd ed.), Architectural Press is an imprint of Elsevier, Oxford, 2008.
- [19] P. Littlefair, J. Lynes, Design method for daylighting, Architects' Journal 07(12) (1995) 38-39.
- [20] BSI, BS 6262-2:2005, Glazing for buildings — Part 2: Code of practice for energy, light and sound, British Standard Institute, London, 2005.
- [21] The Society of Light and Lighting, Lighting Guide 2: Hospitals and health care buildings, The Chartered Institution of Building Services Engineers, London, 2000.
- [22] P.J. Littlefair, Designing with innovative daylighting, Construction Research Communication Ltd, Watford, 1996.
- [23] N. Ruck et al , Daylighting in Buildings, a source book on daylighting systems and components, International Energy Agency, Lawrence Berkeley National Laboratory, Berkeley, 2000.
- [24] P. Littlefair, Developments in innovative daylighting, Information paper, Building Research Establishment, Watford, 2000.
- [25] D. Phillips, Lighting Modern Buildings, Architectural Press, Oxford, 2000.
- [26] A. Soler, P. Otezia , Light Shelf Performance in Madrid, Spain, Building and Environment 32(2)(1997) 87-93.
- [27] E. Vine, E. Lee, R. Clear, D. DiBartolomeo, S. Selkowitz S, Office worker response to an automated Venetian blind and electric lighting system: a pilot study, Energy and Buildings (1998) 28 205-218.
- [28] S.Y. Koo, M.S. Yeo, K.W. Kim KW, Automated blind control to maximize the benefits of daylight in buildings. Building and Environment, 45 (2010) 1508–1520.
- [29] E.S. Lee, D.L. DiBartolomeo, S.E. Selkowitz, Thermal and daylighting performance of an automated Venetian blind and lighting system in a full-scale private office, Energy and Buildings 29 (1998) 47-63.
- [30] S.T. Claros, A. Solera, Indoor daylight climate—influence of light shelf and model reflectance on light shelf performance in Madrid for hours with unit sunshine fraction. Building and Environment, 37 (2002) 587-598.
- [31] C.E. Ochoa, I.G. Capeluto, Evaluating visual comfort and performance of three natural lighting systems for deep office buildings in highly luminous climates. Building and Environment, 41(2006) 1128-1135.

- [32] P. Xue, C.M. Mak, H.D. Cheung, New static lightshelf system design of clerestory windows for Hong Kong, *Building and Environment* 72 (2014) 368-376.
- [33] S. Olbina, J.Hu, Daylighting and thermal performance of automated split-controlled blinds. *Building and Environment* 56 (2012) 127-138.
- [34] CIBSE, *The SLL Lighting Handbook*, The Society of Light and Lighting, Chartered Institution of Building Services Engineers, London, 2009.
- [35] A. Hashemi, Thermal Shutter System, International Patent No. PCT/EP2012/051803, WIPO, 2012.
- [36] A. Hashemi, S. Gage, Technical issues that affect the use of retrofit panel thermal shutters in commercial buildings, *Building Services Engineering Research and Technology* 35(1) (2014) 6-22. (doi: 10.1177/0143624412462906)
- [37] W. O'Brien, K. Kapsis, A.K. Athienitis, Manually-operated window shade patterns in office buildings: A critical review, *Building and Environment* 60 (2013) 319-3388.
- [38] G.Y.Yun, H. Kim, J.T. Kim, Effects of occupancy and lighting use patterns on lighting energy consumption, *Energy and Buildings* 46 (2012) 152-158.
- [39] P.K. Soori, M.Vishwas, Lighting control strategy for energy efficient office lighting system design, *Energy and Buildings* 66 (2013) 329-337.
- [40] A. S. Choi, K. D. Song, Y. S. Kim, The characteristics of photosensors and electronic dimming ballasts in daylight responsive dimming systems, *Building and Environment* 40 (2005) 39-50.
- [41] L. Sanati, M. Utzinger, The effect of window shading design on occupant use of blinds and electric lighting, *Building and Environment* 64 (2013) 67-76.
- [42] P. Littlefair, *Retrofitting solar shading*, Building Research Establishment, Watford, 2002.
- [43] CIBSE, *How to manage overheating in buildings*, A practical guide to improving summertime comfort in buildings. Chartered Institution of Building Services Engineers, London, 2010.
- [44] CIBSE, *Design for improved solar shading control Engineering*, Chartered Institution of Building Services Engineers, London, 2006.

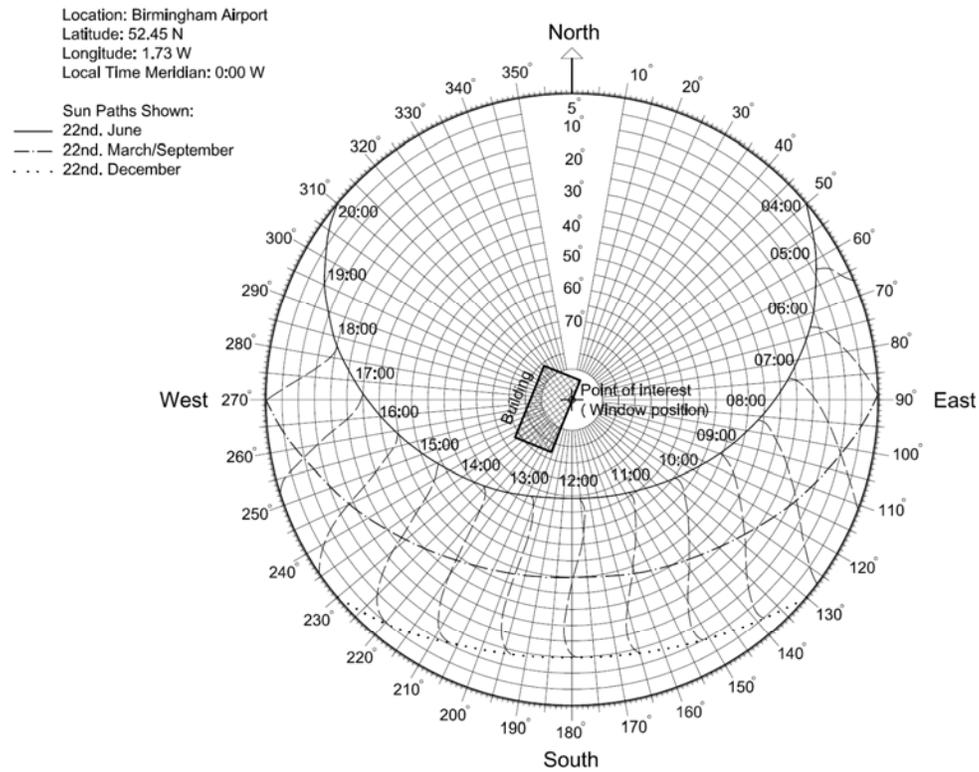
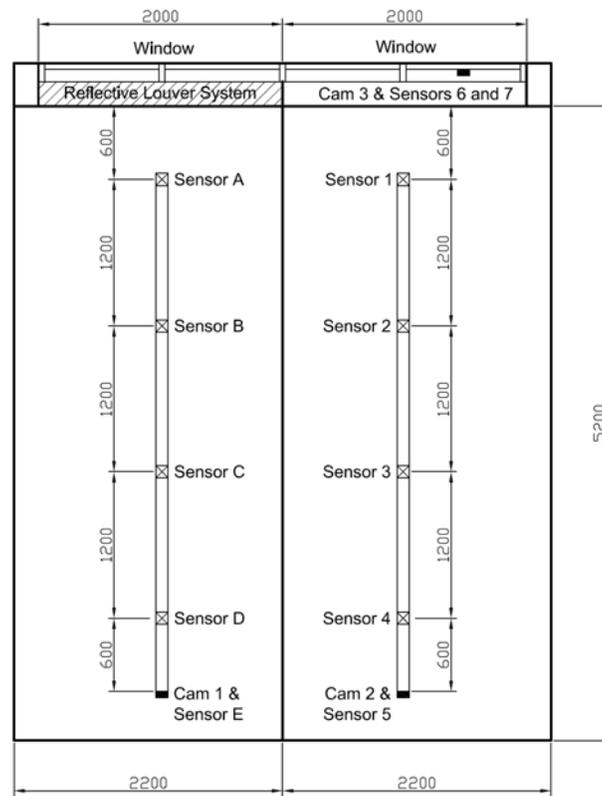


Figure 1: Sun path diagram and position of the tested windows in the case study building.



Figure 2: panoramic view of the landscape in front of the tested windows.



Window sill height: 900mm from FFL  
 Window head height: 2100mm from FFL  
 Ceiling height: 2300mm from FFL

Figure 3: Positions of the sensors and cameras in the test and reference rooms.



Figure 4: View of the rooms and positions of data loggers and cameras.



Figure 5: 300mm louvers made from timber. One face of the louvers was covered with reflective aluminium tapes.

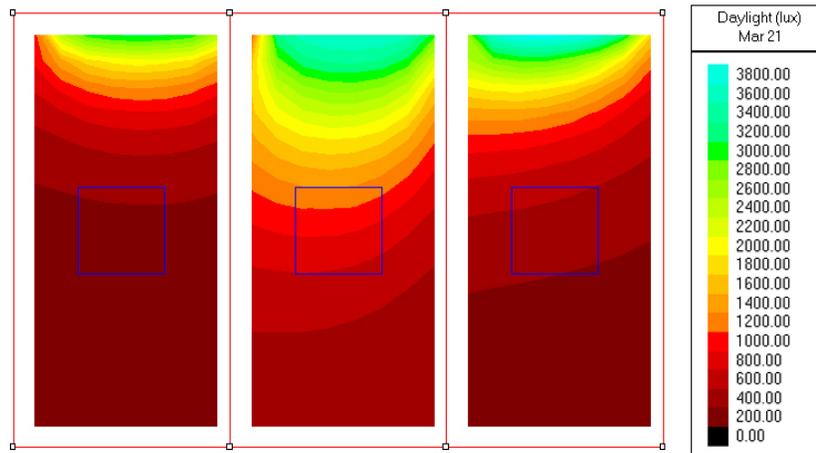


Figure 6: IES results for the bare window for overcast (left) and clear sky at 9am (middle) and 12pm (right).

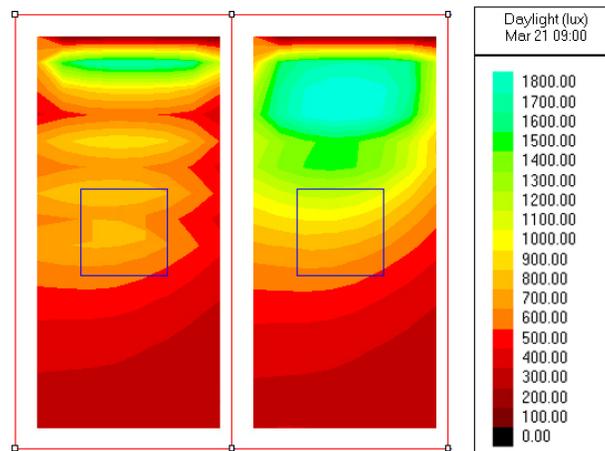


Figure 7: Equally spaced horizontal (left) and -15 degrees tilted (right) louvers under clear sky.

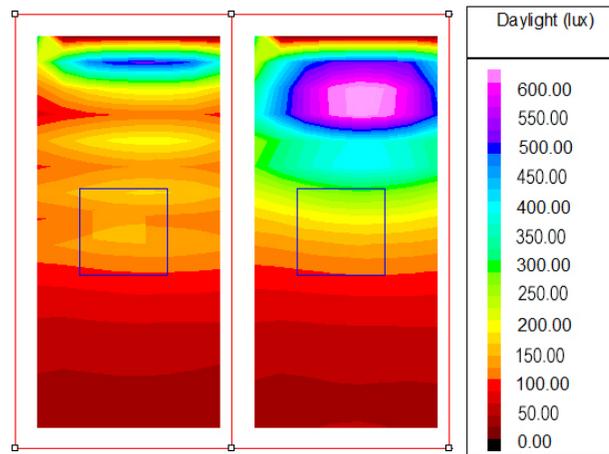


Figure 8: Equally spaced horizontal (left) and -15 degree tilted (right) louvers under overcast sky.

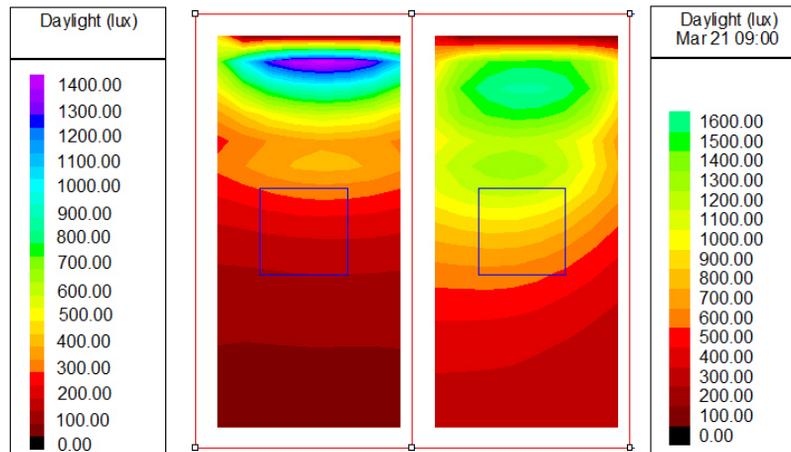


Figure 9: -15-degree tilted light shelf. Left: Overcast sky; Right: Clear sky.



Figure 10: Louvers in light-shelf (left) and sunshade (right) modes.

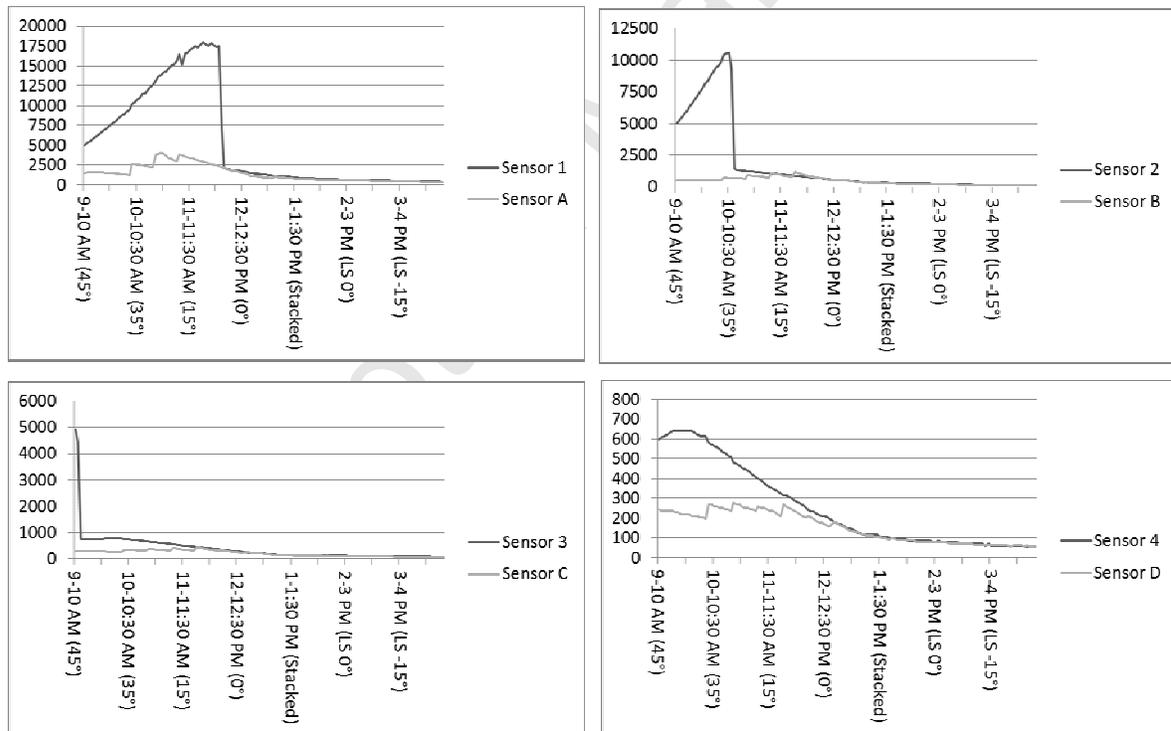


Figure 11: Direct comparison between the results in the test and reference rooms under sunny and clear sky conditions.

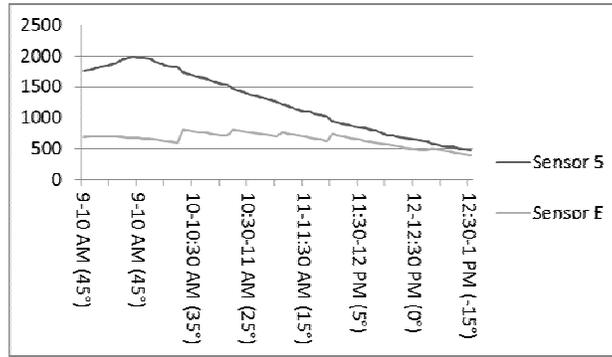


Figure 12: Vertical illuminance at the back of the test and reference rooms under clear sky conditions.

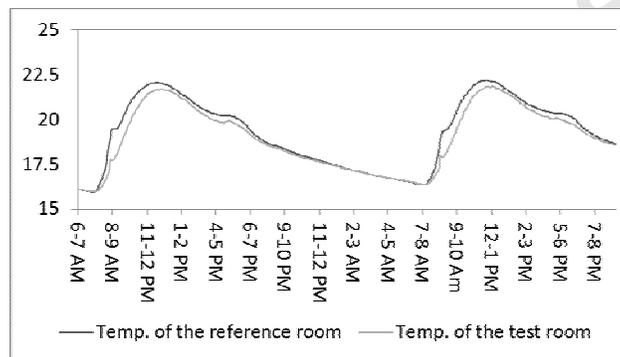


Figure 13: Delayed rise of temperature in the test room for two continuous days under sunny sky conditions.

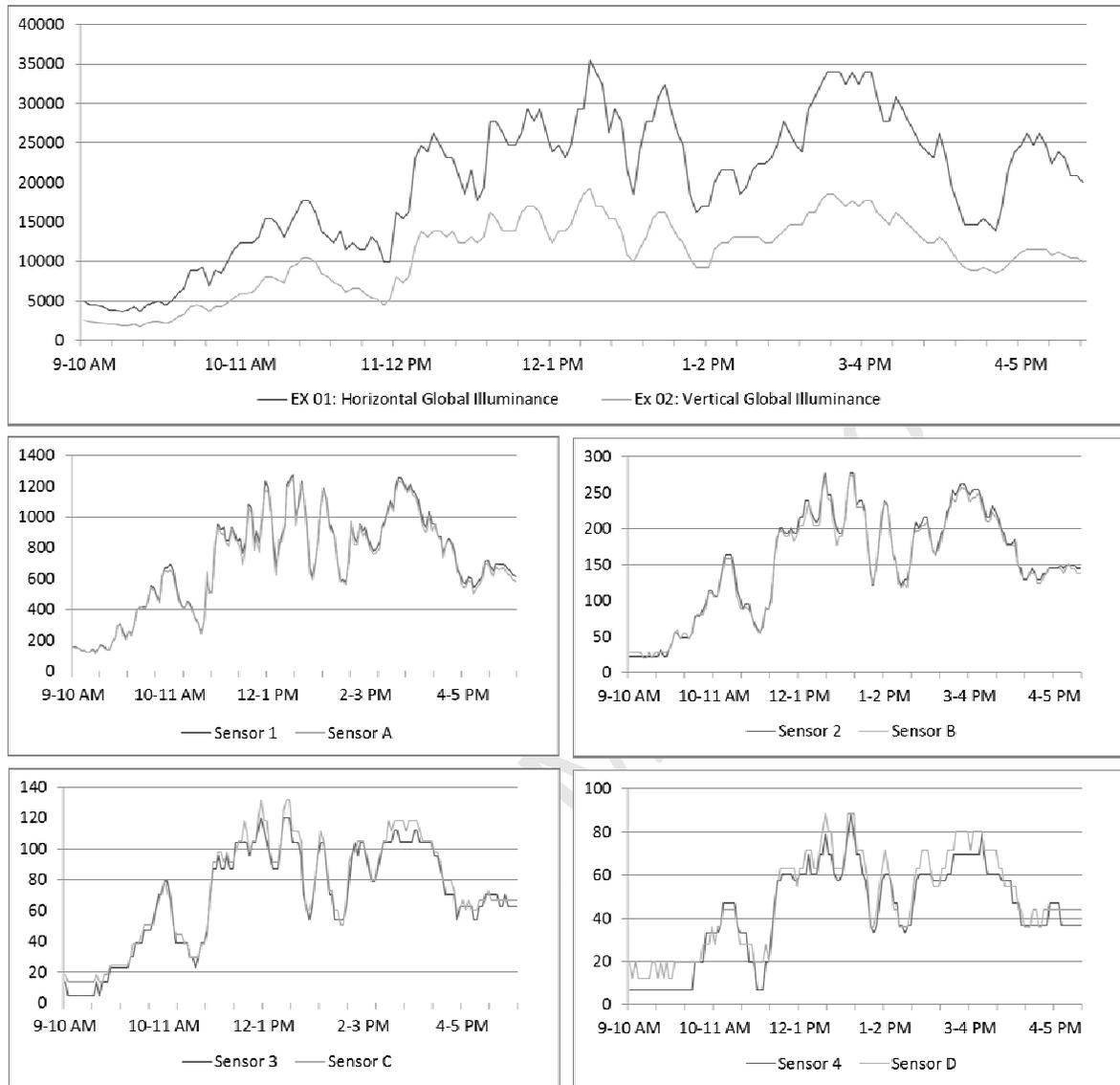


Figure 14: System in light-shell mode (-15 degrees tilted) under overcast sky conditions.

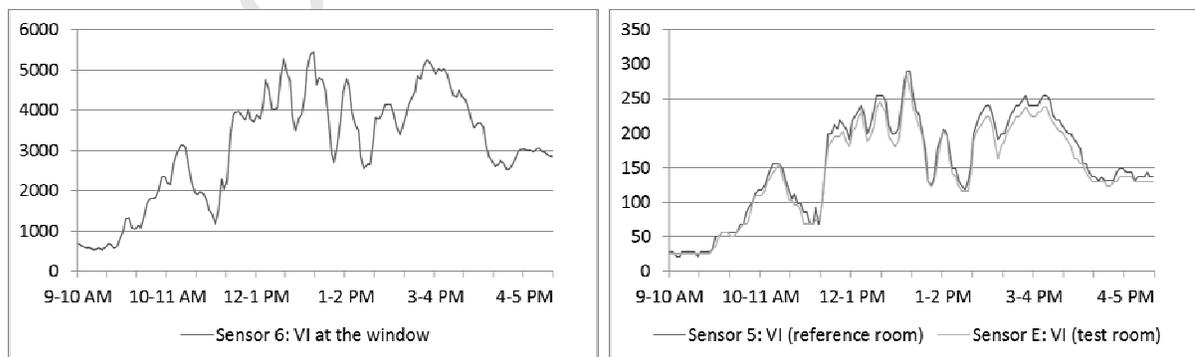


Figure 15: Vertical illuminance (VI) at the window (left) and at the back of the test and reference rooms (right) under overcast sky conditions.

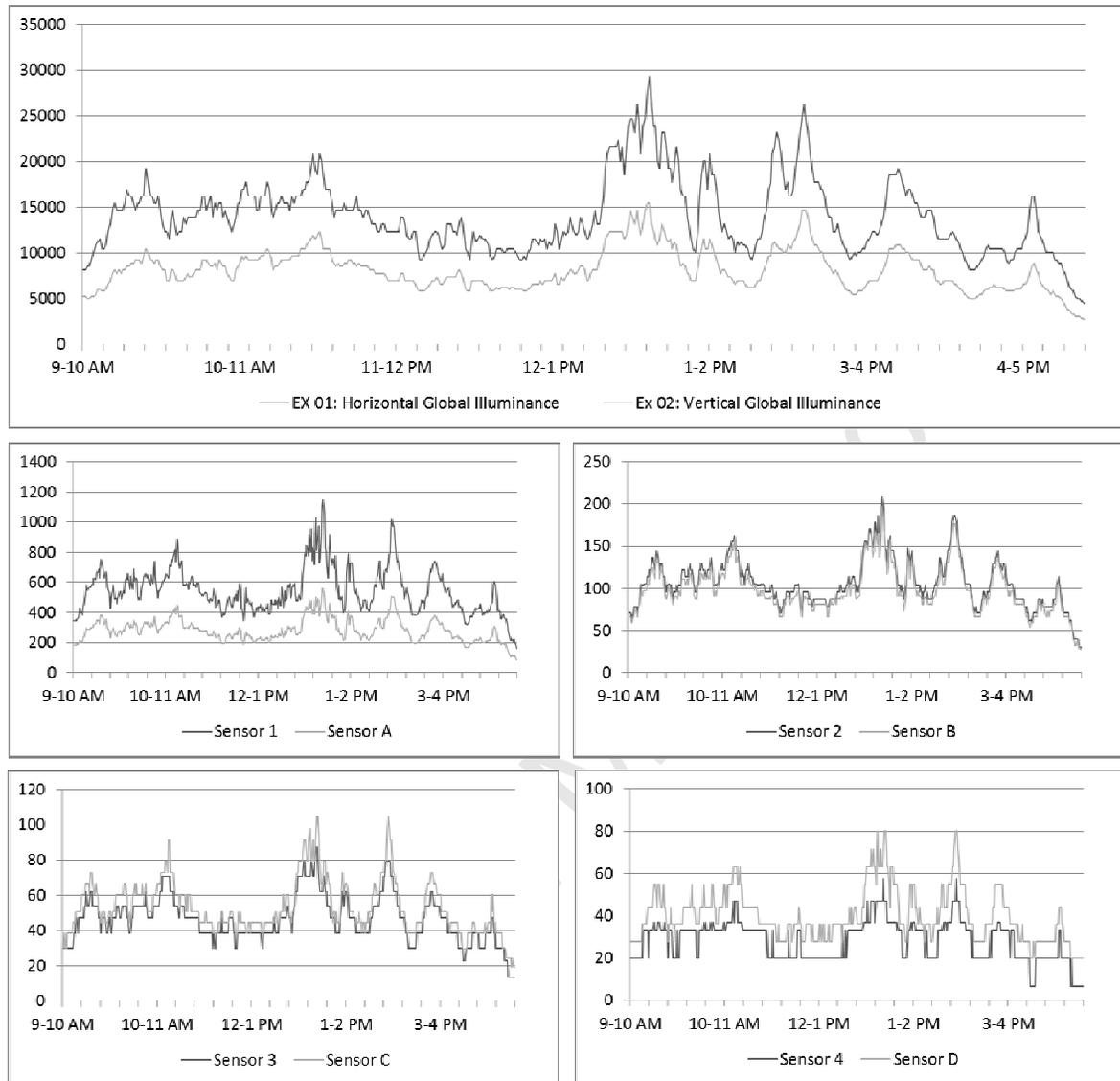


Figure 16: Equally spaced -15 degree tilted louvers under overcast sky conditions.

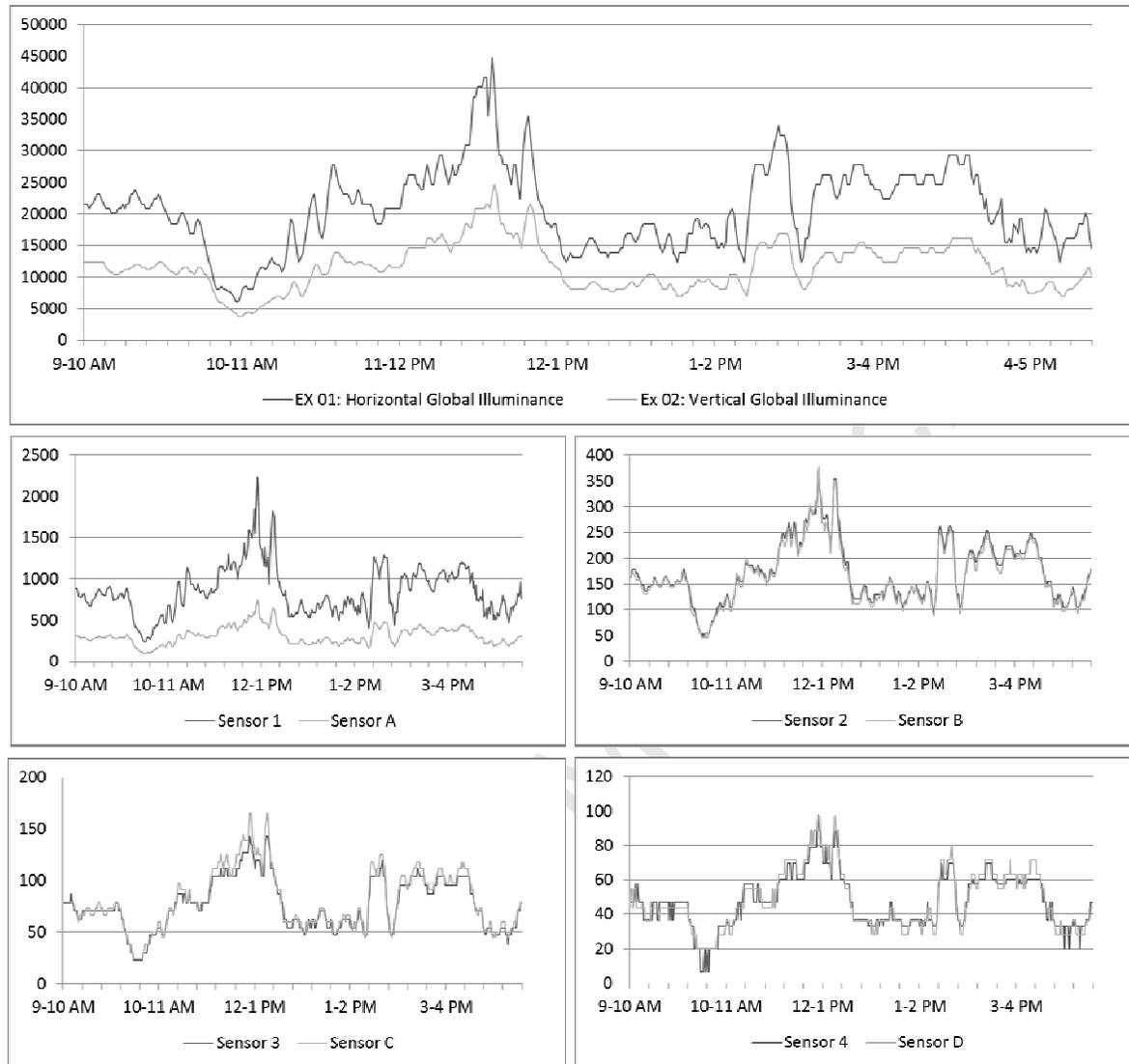


Figure 17: Equally spaced horizontal louvers under overcast sky conditions.

Time	Louver angles (degrees)
9:00-10:00 am	45°
10:00-10:30 am	35°
10:30-11:00 am	25°
11:00-11:30 am	15°
11:30-12:00 pm	5°
12:00-12:30 pm	0°
12:30-1:00 pm	-15°
After 1:00 pm	No direct sunlight on the window

Table 1: Minimum angle of louvers to block the direct sunlight from 9am to 1:00pm.

Time	Day 1		Day 2		Day 3	
	Areas close to the windows	Areas at the back of the room	Areas close to the windows	Areas at the back of the room	Areas close to the windows	Areas at the back of the room
Room	Average illuminance (lux)					
Office	162	24	450	50	87	8
Test Room	4048	327	3400	390	3700	310

Table 2: Comparison between available daylight in the office and the test room in sunny conditions.

Time	Sensor 1	Sensor 2	Sensor 3	Sensor 4	Sensor A	Sensor B	Sensor C	Sensor D
9-10 AM	1160.0	223.7	96.7	61.0	602.0	206.8	111.4	82.9
10-11 AM	1359.1	264.3	117.8	73.5	706.9	245.9	135.0	101.7
11-12 PM	1073.6	209.1	90.7	55.0	557.3	191.5	102.8	76.4
12-1 PM	998.3	198.0	86.6	49.8	522.4	182.2	97.9	72.7
1-2 PM	1556.9	298.3	131.9	79.4	804.4	277.6	152.1	116.2
2-3 PM	1295.2	256.1	112.6	69.6	678.7	236.7	127.8	97.5
3-4 PM	1095.7	211.2	90.8	53.5	565.1	196.1	105.6	78.1
4-5 PM	805.1	153.2	64.3	34.3	413.7	141.9	77.6	57.8

Table 3: Average available daylight in different zones of test and reference rooms for a typical double glazed window under overcast sky conditions (lux)

Time	Sensor 1	Sensor 2	Sensor 3	Sensor 4	Sensor A	Sensor B	Sensor C	Sensor D
9-10 AM	15388.4	15730.5	2559.3	1335.3	3115.3	1095.9	605.5	474.1
10-11 AM	27437.9	6858.3	1430.2	1058.1	6393.0	1609.9	739.3	546.1
11-12 PM	33673.5	1879.5	975.3	693.8	6329.8	1970.5	787.6	506.7
12-1PM	3399.5	1146.1	581.5	410.2	2888.9	1129.0	546.6	364.2

Table 4: Average available daylight in different zones of test and reference rooms for a typical double glazed window under sunny conditions (lux)

Room Conditions	Manual light switches + Manual blinds	Electric light dimmer system + Manual blinds
Sky Conditions	Light dimmer + Reflective Louver System (potential savings in comparison)	
Sunny conditions	90.5%	40.5%
Overcast sky	58.0%	8.0%
Clear sky without direct sunlight	0.0%	0.0%

Table 5: Potential savings in the case study building for various conditions when electric light controls are used in conjunction with the reflective louver system.

**Highlights:**

Reflective louvers potentially reduce the need for artificial lighting by improving daylight distribution in the building.

The tested system reduced the need for artificial lighting by 60%.

The tested device works optimally under sunny conditions.

The tested system is considerably effective under overcast sky conditions.

The tested system delayed the air temperature rise by blocking/reflecting the sunlight reducing the cooling loads.

Accepted Manuscript