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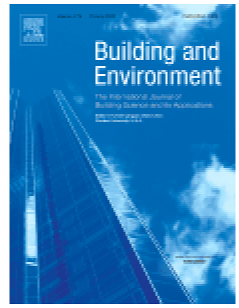

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The Potential of Circadian Lighting in Office Buildings Using a Fibre Optics Daylighting System in Beijing

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Abstract:

This study presents an investigation of circadian lighting potential for a fibre optics daylighting system (FODS) in a single office in Beijing, China. Research methods included the monitoring of FODS daylighting performance during a 11-month period, the indoor lighting simulations at the horizontal workplane and vertical planes using a single office model, and thus the theoretical calculations of circadian stimulus brought by the FODS. Key findings are as follows: There is a high possibility that a proper level of circadian light at a windowless workspace could be achieved through applying the FODS in northern China. With this FODS, the non-visual effect of lighting (circadian system entrainment) can be attained when a standard lighting requirement was met at the horizontal workplane based on occupants' visual performance in this office. Compared with typical artificial lighting systems, the FODS can deliver circadian light in a more efficient way. In addition, it can be found that the application of FODS system would benefit office workers in terms of both visual and non-visual aspects. It is the first study to investigate the non-visual performance of a fibre optics daylighting system.

Keywords:

Circadian lighting, Fibre optics daylighting system (FODS), Daylighting monitoring, Simulation, Office building, Beijing.

1. Introduction

1.1 Daylight utilization in offices

As a critical environmental factor at workspaces, daylighting can significantly affect occupants' productivity, overall satisfactions, and health/well-being [1, 2, 3]. Studies of the effect of daylighting on human performances are receiving increasing attention in office buildings, especially in Europe and North America. A field survey in ten Dutch office buildings showed that workers' visual comfort and well-being are substantially associated with configurations and installations of external windows (delivering daylighting and view) [4]. A Swiss human experiment further demonstrated that occupants' visual performance, mood and alertness can be improved by daylighting [5]. In USA, a study [6] first showed that more exposure to daylight tends to improve sleep quality and overall health of office workers. Later, a series of American office surveys enhanced the importance of daylighting and its capabilities of improving stress, mood and sleep quality of occupants, particularly in winter when the daylight availability is lower [7, 8]. Very recently, two new studies that were conducted in China started to test the daylight impact on the performances of East Asian workers [9, 10]. These findings strongly suggested that more emphasis should be placed on providing occupants with more daylight exposure in offices.

1.2 Applications of fibre optical daylighting system

Daylight can be transported from outside by collating it and guiding it through a light guiding media over long distances into rooms in the depth of the building [11]. There have been many daylighting systems demonstrated to utilize the daylight for indoor lighting [12, 13]. Among these systems, the fibre optical daylighting system based on solar concentrators and fibre optical transmission has attracted more attentions, due to the fact that it can offer reliable daylighting with broad applicability and high effectiveness [14, 15]. Over 10 years ago, the preference for daylight and the health consciousness have stimulated more interest in the investigations into the fibre optical daylighting systems, with a research focus on the system design and technical developments including collection, storage, transmission and distribution of daylight. At a subtropical location, one early study developed an innovative cassegrain solar concentrator system using a chromatic lens to reduce UV and IR of daylight [16]. An optical fibre solar concentrator was proved as effective at a tropical location, consisting of a PMMA (Polymethylmethacrylate) plate and 150 pieces of three-color fluorescent fibres [17]. In north-east Asia, a simple system adopted a parabolic profile to deliver a stream of high-density solar flux into the interior using the fibre optics [18]. Under a similar climate as the study [18], Xue et al. proposed a novel sunlight concentrator including a mirror image co-focus compound parabolic concentrator, which can significantly enhance the feasibility of fibre optical daylight guiding system [19]. Interestingly, Han et al. produced a similar daylighting system in England (dominated by overcast sky), which consists of dish concentrator(s), a dual-axis solar tracker and light guides including optical fibre cables [20]. To improve the uniform distribution of daylighting in a large-scale office building, a Korea study presented an approach consisting of a parabolic mirror, a Fresnel lens and a trough compound parabolic concentrator (CPC), and supplementary LED light [21]. Clearly, this was regarded as a hybrid daylighting system due to the application of LED. In north China, Song et al. developed a daylighting system consisting of optical fibres and a sun-tracking model with high concentrating level and tracking precision, and thus led to a good tracking performance [22]. Later, an innovative system based on the parallel mechanism was proposed at the same location [23]. A light-guiding plate (LGP) for the utilization of sunlight has been proved with a higher performance of lighting and uniformity [24]. A cost-effective optical fibre daylighting system was produced in South Korea, including a compound parabolic concentrator (M-CPC) and plastic optical fibres (POFs) [25]. This system had high tolerance for various input angle of sunlight and demonstrated an optical efficiency of up to 84%. A brief note in China reported that the shortpass dichroic mirror (SDM) can effectively filter out up to 64% of infrared ray from high flux, and therefore produce small losses of visible spectrum of natural light [26]. Muhammad et al. examined the indoor lighting performance of a fibre optic daylighting system under various sky conditions (sunny, intermediate and overcast) in Malaysia and several design benchmarks for local architects and engineers were thus established [27]. Recently, to increase illuminance uniformity indoors, one simulation study proposed an optimised optical fibre daylighting system using an eight-fold Fresnel lens as the primary optical element (POE) and a Bi-layer prismatic diffuser [28]. An American measurement showed a faceted secondary concentrator for a fiber-optic hybrid solar lighting system offers a distinct advantage of higher sun angle tolerance and hence a low-accuracy tracker for the mobile application [29]. Using POFs, another low cost daylighting system was proposed in North Africa [30]. This system adopted a new patented mechanical part for securing the fibre optic bundle at the focal point while ensuring a three level of heat filtration and uniform illumination. The design and optimization of optic fibre daylighting system was further conducted based on a novel linear Fresnel lens achieved through the conservation of optical path length and edge ray theorem [31]. In addition, two new studies were implemented in a Mediterranean region: one reported a small scale linear Fresnel reflector (SSLFR) applied in an optical fibre daylighting system [32], while another one focused on the indoor lighting control with the occurrence of optical fibre daylighting system [33]. Apparently, the application of optic fibre daylighting system is still one of significant advanced passive solutions to effectively apply daylighting in buildings.

1.3 Circadian lighting

Recently, with the advent of enhanced emphasis on improving occupants' health and wellbeing at workspaces [34], non-visual performances (physiological and psychological aspects) of daylighting have been targeted as a significant research focus in the field of environmental study [35]. As pioneers, several studies [9-10, 36] have preliminarily investigated the window system, daylighting, and their impact on human non-visual performance. It seems that a new trend for justifying the performance of any daylighting systems will be their functions of delivering proper lighting on basis of occupants' health and wellbeing [35]. Thus, circadian lighting [37, 38] was produced to indicate the impact of lighting on human circadian rhythm. Based on light spectral distribution and lighting levels measured near human' eyes, Circadian Light (CL_A) and Circadian Stimulus (CS) were defined according to the theories [37, 38]. The two values were adopted as indicators of the nocturnal melatonin suppression due to the spectral response of the human circadian system [38]. Different from the illuminance based on the photopic luminous efficiency function [V(λ)], CL_A is irradiance weighted by the spectral sensitivity of the retinal phototransduction mechanisms stimulating the response of the biological clock [37]. The equations of CL_A calculation are given as follows [37, 38]:

$$CL_A = 1548[\int M_{C_\lambda} E_\lambda d\lambda + (a_{b-y}(\int \frac{S_\lambda}{mp_\lambda} E_\lambda d\lambda - K \int \frac{V_\lambda}{mp_\lambda} E_\lambda d\lambda) - a_{rod}(1 - e^{\frac{-\int V'_\lambda E_\lambda d\lambda}{RodSat}}))],$$

$$\text{If } \int \frac{S_\lambda}{mp_\lambda} E_\lambda d\lambda - K \int \frac{V_\lambda}{mp_\lambda} E_\lambda d\lambda) > 0 \qquad (1);$$

$$CL_A = 1548 \int M_{C_\lambda} E_\lambda d\lambda,$$

$$\text{If } \int \frac{S_\lambda}{mp_\lambda} E_\lambda d\lambda - K \int \frac{V_\lambda}{mp_\lambda} E_\lambda d\lambda) \leq 0 \qquad (2);$$

Where, CL_A is the circadian light. The constant, 1548, sets the normalization of CL_A, so that 2856K blackbody radiation at 1000 lux has a CL_A value of 1000;

E_λ is light source spectral irradiance distribution;

Mc_λ is ipRGC melanopsin sensitivity (corrected for crystalline lens transmittance);

S_λ is S-cone fundamental;

mp_λ is macular pigment transmittance;

V_λ is photopic luminous efficiency function;

V'_λ is scotopic luminous efficiency function;

RodSat is half-saturation constant for bleaching rods = 6.5W/m^2;

K =0.2616, representing the interactions among photoreceptor types. This value has been set so the crosspoint of the b–y (blue-yellow) channel is at 507 nm, consistent with independent estimates of unique green;

$a_{b\text{-}y}$ = 0.7000 and a_{rod} = 3.3000, which represent the interactions among photoreceptor types (b-y: blue-yellow channel, and rods).

In addition, CS can be produced via the transformation of CL_A using the following algorithm [38]:

$$CS = 0.7 - \frac{0.7}{1+(\frac{CL_A}{355.7})^{1.1026}} \qquad (3).$$

CS has a range of (0~0.7). The '0' value means the threshold for circadian system activation whilst the response saturation will be achieved at the value of '0.7'. CS is directly proportional to nocturnal melatonin suppression after one-hour exposure (0% to 70%) [37]. As discussed in a field study in offices [35], CS = 0.3 has been recognized as the minimum requirement to reduce sleepiness and increase vitality and alertness of workers.

1.4 Research question and the present study

Based on the discussions in section 1.2, past and recent bodies of research emerged in terms of fibre optics daylighting system (FODS) were focused on the efficiency of the system and solutions to technical challenges in order to bring daylight into deep plan of office buildings. However, no research activities can be found according to the feasibility to deliver circadian lighting through the FODS. Therefore, given the current situation of optical fibres daylighting system application, a new research question occurs: is it possible to apply this system to improve occupants' circadian performances in an office without windows?

In this article, using on-site monitoring, computational simulations, and theoretical calculations, a study was conducted to verify the feasibility and the potential of one fibre optics daylighting system (FODS) to deliver circadian light in a windowless office in Beijing. Three main parts were presented as follows. Section 2 gives materials and methods, including the general daylight availability in Beijing, the hardware system and procedures of daylighting monitoring of FODS in a laboratory, a typical single office model and relevant design methods and simulations of its indoor lighting system attached with this FODS, and the metric of circadian lighting. In addition, section 3 gives the analysis of monitored daylighting performance of FODS, and a comprehensive analysis of visual performance (illuminances) and non-visual potential (Circadian Lighting) of this FODS in the single office. Finally, key findings of FODS performance were discussed and summarized in the section 4.

2. Materials and methods

2.1 Climates and daylight availability in Beijing

This investigation was implemented in Beijing, China (Latitude: 39.9042° N, Longitude: 116.4074° E). Beijing has a humidity continental climate (www.weatherbase.com). July has the highest average temperature of 26°C (79°F), while the coldest month is found in January with the temperature of -3.3°C (26°F). Beijing receives the annual sunshine time of 2,671 hours, and the monthly percentage sunshine time ranging from 47% in July to 65% in January. To further understand the daylight availability in Beijing, an analysis of the monthly and hourly unobstructed horizontal illuminances was produced using local weather data (achieved from the database of EnergyPlus: https://energyplus.net/weather-region/asia_wmo_region_2) (Figure 1).

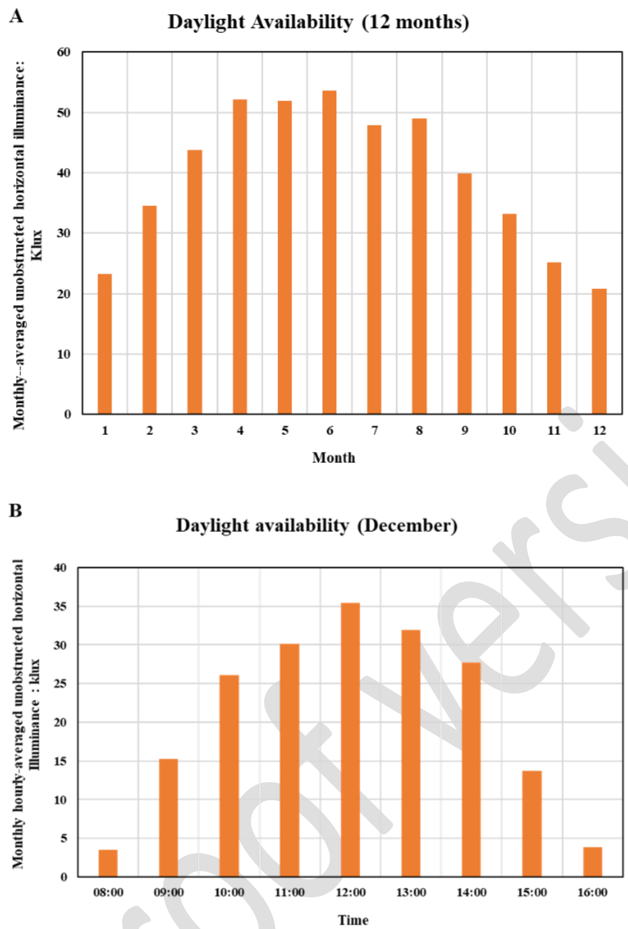

Figure 1. Daylight availability in Beijing (Latitude: 39.9042° N, Longitude: 116.4074° E); A: monthly-averaged unobstructed horizontal illuminances; B: Hourly-averaged unobstructed horizontal illuminances in December.

As displayed in Figure 1 (A), for the monthly-averaged unobstructed horizontal illuminance, June has the highest value of 53.61 Klux, while the lowest value (20.85 Klux) is found in December. Apparently, the monthly-averaged illuminances from April to September are generally higher than those from October to March. Therefore, if a daylighting system (e.g. optical fibre system) is expected to provide sufficient indoor light for supporting normal office work, autumn and winter would be the typical period for system planning and performance monitoring. Thus, this study has adopted December as the baseline of daylighting potential analysis since it stands for the worst situation. Figure 1 (B) presents the monthly hourly-averaged unobstructed horizontal illuminance in December. General variations in this month are as follows. The illuminance rises from 8:00 (3.52 Klux), and peaks at 12:00 (35.44 Klux), and then decline towards 16:00

(3.86 Klux). Taking the peak as a reference, percentage differences between peak and early morning or late afternoon are round 90%. The big difference could be explained by the fact that the clear sky is dominated in winter period in Beijing. In addition, it can be found that there are no big differences of daylighting availability between morning and afternoon in winter Beijing.

2.2 Daylight monitoring: a fibre optics system

In this study, the performance of a fibre optics daylighting system (Himawari: www.himawari-net.co.jp) was monitored in a laboratory of Tsinghua University in Beijing (Figure 2). The daylight monitoring was conducted based on an integrated system including FODS, an integrating sphere and a spectrum testing equipment.

The FODS studied was composed of a 12-lens sunlight collector (XD-50S/12AS), control unit and optical fibre cables connected with the sunlight collector. The sunlight collector can accurately track sunbeam through an automatic tracking system including the control unit and an optical sensor to detect solar position. Thus, this sunlight collector can achieve the maximum efficiency according to the active daylight utilization. Optical fibre cables were used to transmit daylight from the collector into indoor lighting distribution system. Single optical cable has a bundle of six optical fibres inside, each of which has a diameter (φ) of 1 mm. Two optical cables (length: 9 m) were applied to connect the12-lens sunlight collector with an integrating sphere in the laboratory. This integrating sphere (diameter φ = 1 m) was used to measure the luminous flux of light received from the sunlight collector. During the monitoring, a spectrum testing device was also connected with the integrated sphere. Main components of the spectral device included a digital light colorimeter (XYC-II), a standard light source (12V/4A) with DC power supply, 500-voltage regulator, 1000W AC stabilized-voltage power, and a computer workstation for controlling measurements and processing monitored data. A cuboid case was used to contain the colorimeter and relevant electrical accessories. The spectrum testing system can provide with several types of monitored data of the FODS, such as luminous flux, CCT (Correlated Colour Temperature), and CRI (Colour Rendering Index). All monitored data were analysed and saved in the computer workstation.

Daylight monitoring of this FODS was implemented within normal working time of (8:00~17:00) from 1st March 2008 to 31st January 2009. A time step of 15-minute was used to collect daytime data. When the luminous flux was measured as lower than 51 lm (a threshold was recommended by Himawari FODS), the monitored data were not recorded and further processed due to the very low possibility for daylighting utilization. Data in February was not properly monitored because of the lack of support from the facility management and some system problems occurring with a harsh weather condition.

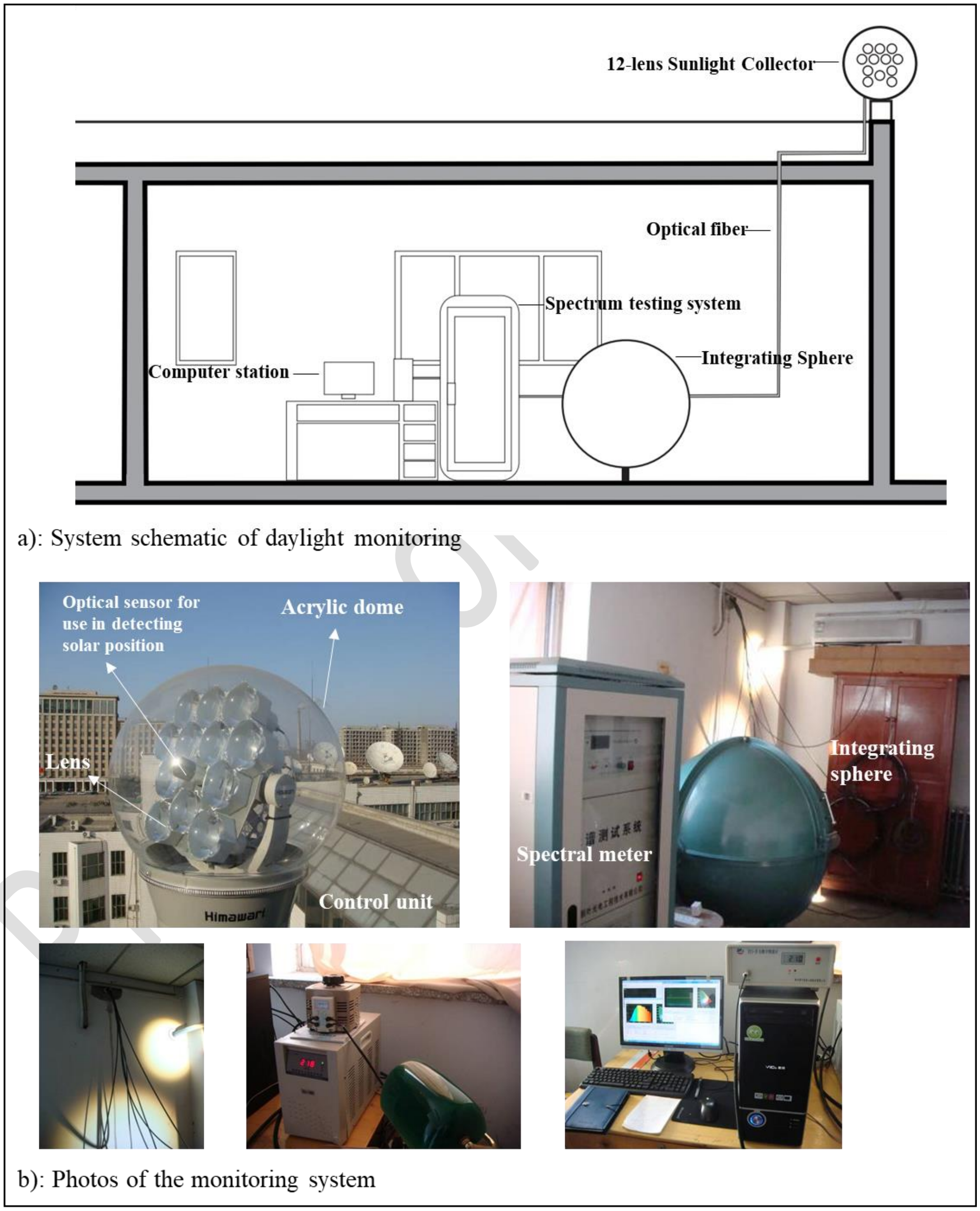

Figure 2. Daylight monitoring of a fibre optics daylight system.

2.3 Lighting design and simulation: single office

This section presents a virtual office model used for lighting simulation and design, with the light source provided by the FODS.

2.3.1 The virtual office model and calculation positions

A typical single office model was defined according to the Design Code for Office Buildings in China [39], with an aim to test possibilities to apply the FODS for lighting. As mentioned in the code, the height of workspace should be more than 2.7m and the area of a single office room should be larger than 10 m^2. Therefore, dimensions of this typical office room were set as 6 × 3 × 3 m. Reflectances of the room surfaces were 0.2 (floor), 0.5 (wall) and 0.7 (ceiling) [40].

The workplane was placed with a height of 0.8 m above the floor, while the height of 1.2 m above the floor was regarded as the level of human eyes when he/she was sitting in an office chair [40]. In this room, the lighting performance was justified based on two types of illuminance: average horizontal illuminance at the workplane (E_H); vertical illuminance at the human eyes (E_V). As displayed in Figure 3, four typical sitting positions A1-4 were selected as calculation points. A1 and A4 were at the corner and centre respectively, while A2 & A3 were the positions near two side-walls. At these positions, vertical illuminance was analysed using two viewing directions, such as E_{v1} (along the width) and E_{v2} (along the length). In a total, eight observation positions were studied through the combination of these sitting positions and viewing directions.

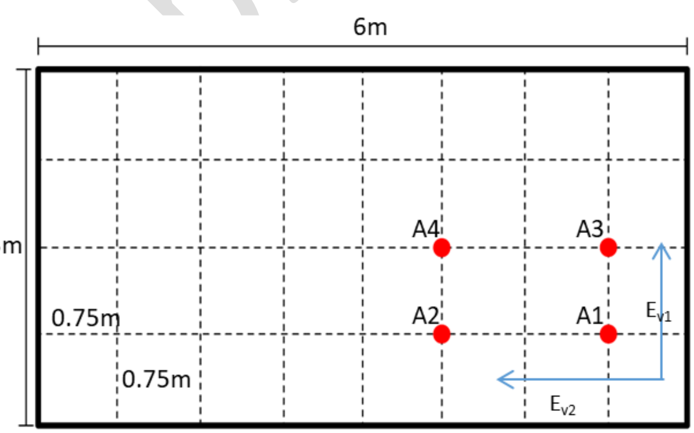

Figure 3. Virtual single office model: plan, calculation positions, and viewing directions.

2.3.2 The design of indoor lighting system

As mentioned in section 1, the research aim in this article is to answer the question of if the optical fibre system can meet the normal illuminance standards and thus improve non-visual performance in terms of human circadian rhythm. In this section, DIALux (www.dialux.com), a professional lighting simulation tool broadly used in lighting industry, was applied to achieve the design of indoor lighting system in this single office, based on lighting requirements at the workplane [40].

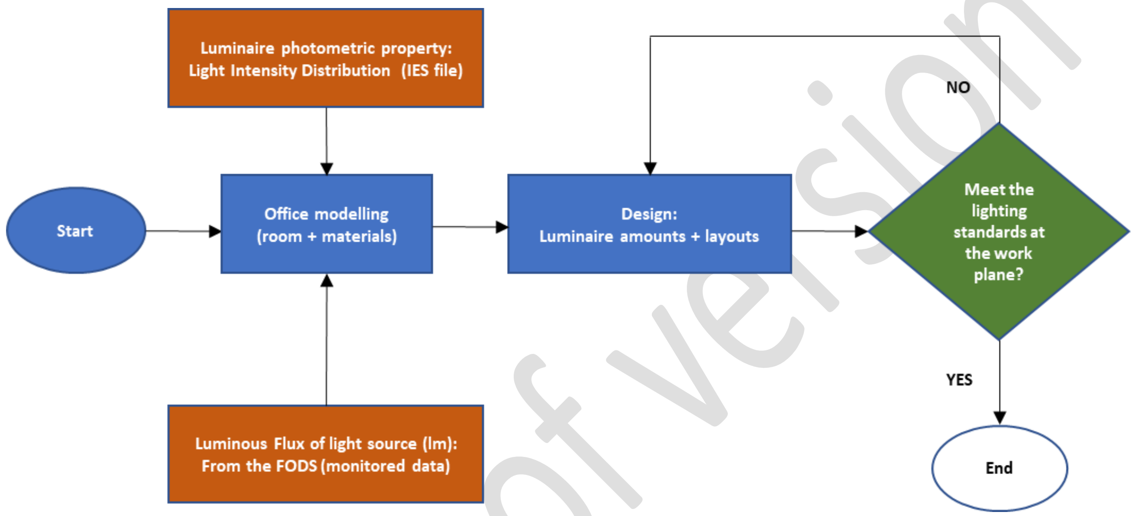

Figure 4. Workflow of the lighting design in this single office (via DIALux).

A workflow to display this design procedure can be found in Figure 4. All design activities were completed using DIAlux. This single office was modelled using DIAlux model editor and relevant surface materials (reflectance) were also applied. Before starting the lighting simulation, two types of required photometric data were inputted, including the luminaire photometric property (Light Intensity Distribution, in IES file), and the luminous flux of light source for the luminaire. As shown in Figure 5, one specific luminaire (Downlight) was used for this lighting design, which is compatible with the FODS and provided by the FODS manufacturer. According to its Light Intensity Distribution (Figure 5), this Downlight luminaire has a narrow beam, which could be determined by the special luminaire configuration to connect the optical fibre of the FODS. In addition, the luminous flux of light source (lm) comes from the monitored data of FODS (section 2.2). In this study, calculations of indoor lighting solutions were based on mean luminous flux achieved through the FODS in December (see Table 1 in section 3.1), which meant the worse situation for daylight utilization. Then, DIAlux can help produce a design solution inlcluding luminaire amounts and layouts. Three levels of standard illuminance at the workplane were used to justify the performance of design solutions according to an office lighting regulation [40], such as 150 lx (low), 300 lx (medium), and 500 lx (high). For each illuminance level, one relevant light layout was defined through DIALux to ensure that the average illuminance at work plane could meet the requirement.

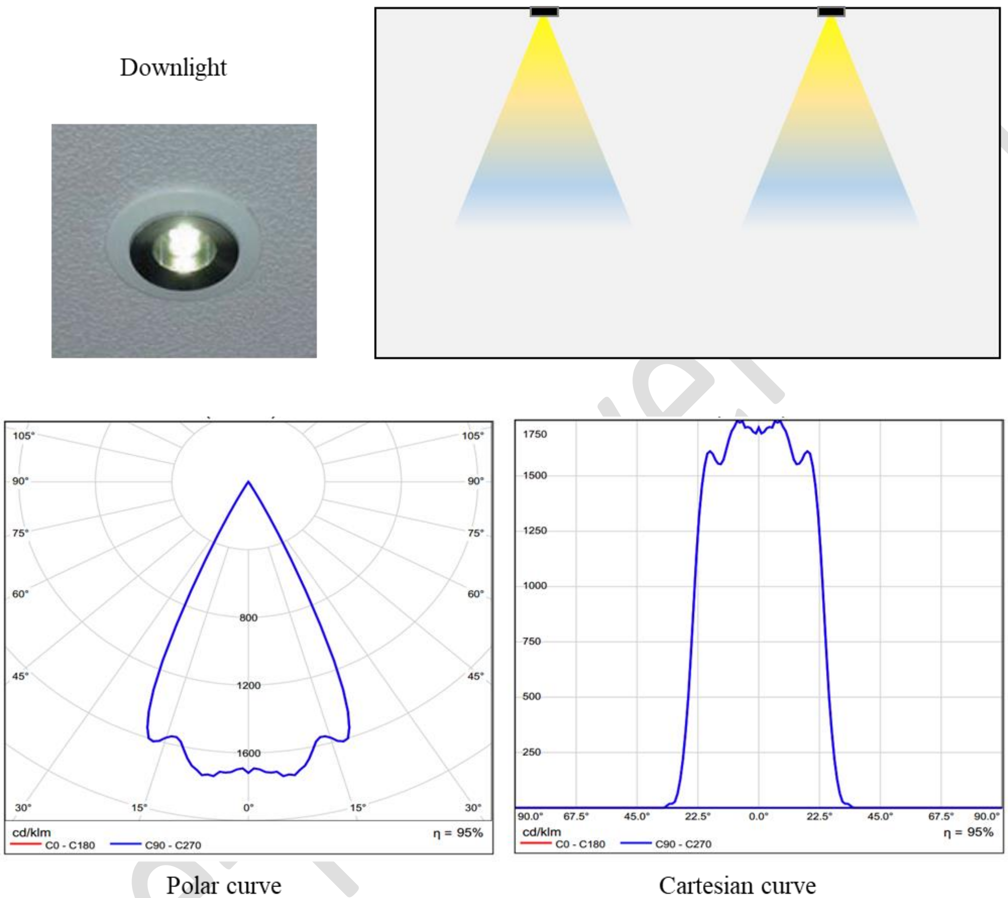

Figure 5. The Downlight used in this office and its light intensity distribution (IES file was provided by the FODS manufacturer).

2.4 Metric of circadian lighting of FODS

As mentioned in section 1.3, Circadian Light (CL_A) and Circadian Stimulus (CS) [37, 38] have been defined as metrics of the impact of lighting on human circadian system. This study adopted CS as an indicator to assess the non-visual performance of the FODS. CS values were calculated based on the monitored FODS data and the equations (1-3). Following the suggestion in an article [35], CS $\geq$ 0.3 can be regarded as the achievement of proper level of circadian lighting in the present study.

3. Results

In this section, based on the recommendation of two studied [41, 42], the monthly-averaged hourly method was adopted to display variations of luminous flux and CCT (section 3.1) and the illuminance (section 3.2) in this office.

3.1 Daylighting performance of the FODS: luminous flux (lm) and CCT (K)

Based on the FODS mentioned above, variations of monitored monthly hourly-averaged luminous flux (lm) were displayed in Figure 6. Apparently, August (summer) and December (winter) have the highest and lowest values, respectively. In general, the hot summer period (July – August) received much higher daylight luminous flux than the winter period (November – January), while the spring period (March – May) has lower values than autumn (September – October). The luminous flux in most months peaked in a period from 11:00 to 13:00. Interestingly, June receives lower values of luminous flux than May and July and has a flat varying trend of monthly hourly-averaged luminous flux across the day. January, March, and April have similar varying trends. As mentioned in section 2.2, no data in February were available. Thus, the general variation of February can be estimated based on the trend of its adjacent months.

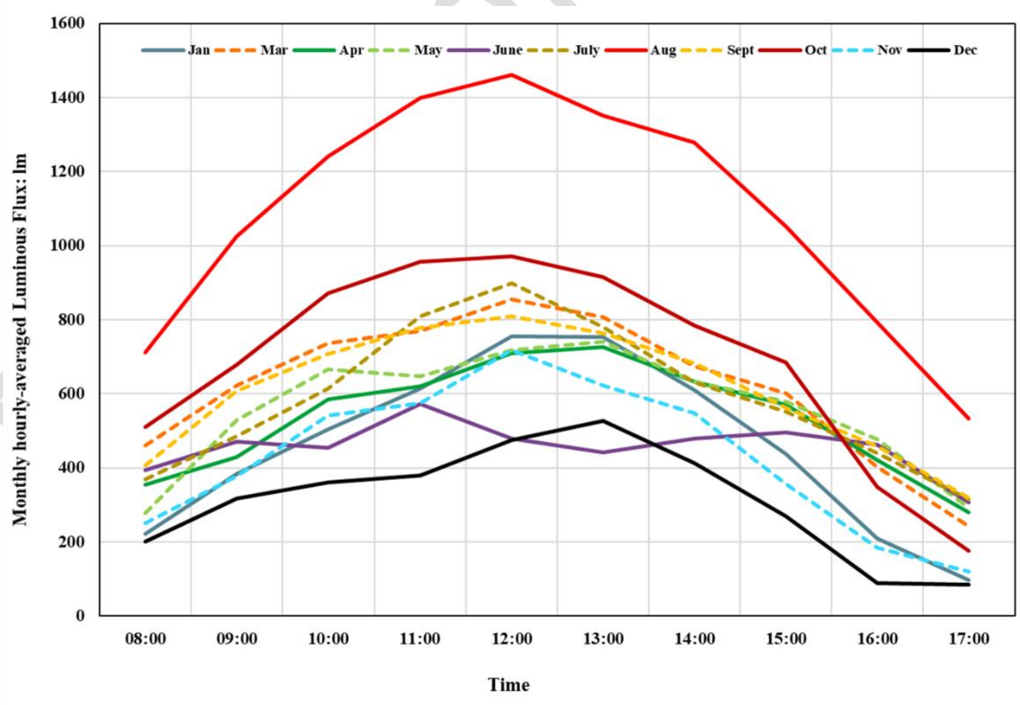

Figure 6. Monthly hourly-averaged luminous flux (lm) of the monitored FODS.

Figure 7 demonstrated monthly hourly-averaged CCT (correlated colour temperature, K), which was achieved from the measured spectrum of daylight. Similar to the luminous flux, August has the highest CCT values among all months monitored. In addition, for most time of the day, CCT in August was found as higher than 5500K. July and September still have the higher CCT values between 5000K and 5500K, while lower CCT values (< 4500 K) were only achieved in December and January. Normally, CCT started to rise from the morning, peaked near the noon, and then dropped towards the evening. Corresponding to the variation of luminous flux, CCT in June has a relatively flat varying trend with the exception of 11:00. This might be explained by the fact that a stable sky condition (i.e. overcast sky) was dominant in June.

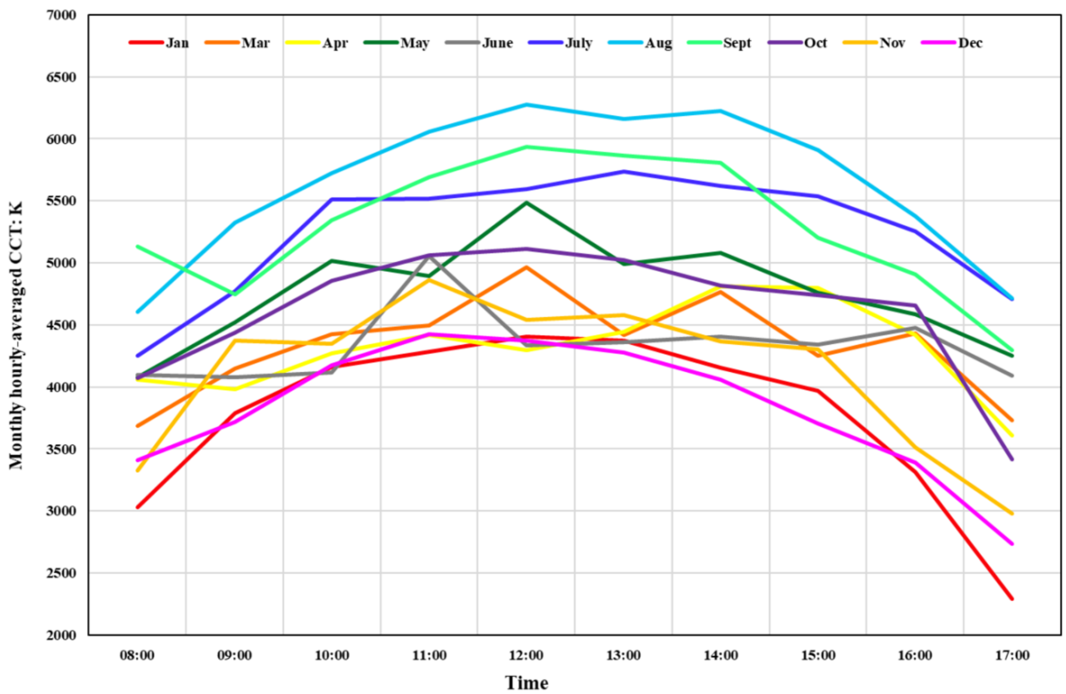

Figure 7. Monthly hourly-averaged CCT (K) of the monitored FODS.

Table 1. Monthly hourly-averaged luminous flux & CCT (±SD) in December.

	Monthly hourly-averaged values in December									
	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00
Luminous Flux (lm)	199.89 ±17.99	318.07 ±16.75	360.74 ±22	379.7 ±21.48	475.69 ±25.88	525.95 ±25.73	412.17 ±21.4	270.16 ±18.61	89.03 ±13.41	85.38 ±17.1
CCT (K)	3409.45 ±114.42	3720.63 ±36.73	4177.63 ±47.33	4423 ±48.08	4376.42 ±46.01	4277.36 ±41.93	4057.36 ±47.96	3706.04 ±60.07	3392.58 ±218	2737.8 ±82.05

Given the discussion above, December has been identified as the period with the lowest possibility to apply daylighting through the FODS. More details of monitored luminous flux (lm) and CCT (K) in December can be found in Table 1. For the luminous flux, December sees the highest value (525.95 lm) at 13:00 and the lowest value (85.38 lm) at 17:00. Morning times tend to have higher luminous flux than afternoon times. As for the CCT, there was the highest CCT (4376.42K) at 12:00 and the lowest CCT (2737.8K) at 17:00. Therefore, the daylight colour in the morning appeared more "colder" than that in the afternoon. Generally, CCT variations of this FODS would support a normal working condition required by standards [40, 43].

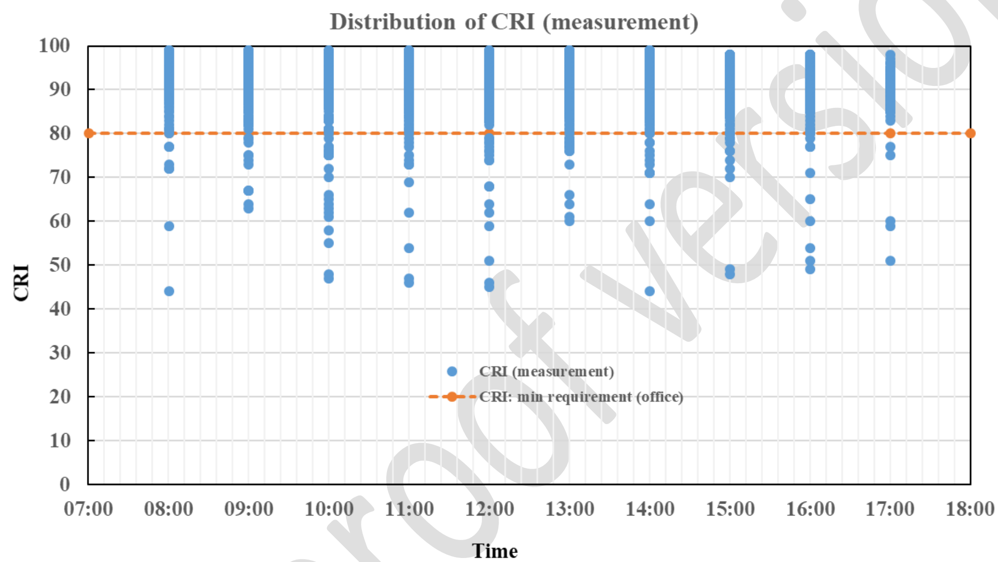

Figure 8. Distrubution of Colour Rendering Index (CRI).

Apart from the luminous flux and CCT, CRI (colour rendering index) values were also calculated from the measured spectral distributions of daylight, based on the requirement of office lighting [40, 43]. As indicated in Figure 8, 97.7% of measured CRI values was found above 80 [40], which can prove that the daylighting delivered by the FODS has an excellent colour rendering ability for indoor use in offices.

3.2 The designed lighting layouts

Following the introduction of section 2.3, in Figure 9, layouts of the luminaire (Figure 5) were designed using DIALux with respect to three illuminance levels (150 lx, 300 lx, 500 lx). The luminaire amounts for 150lx-standard, 300lx-standard and 500lx-standard were 10 (5 × 2), 24 (6 × 4) and 40 (8 × 5) respectively. Thus, the lighting solution for 500lx-standard appeared the most intensive distribution with a distance of 0.6 × 0.75

m, while the 150lx-standard and 300lx-standard layouts have a distance of 1.5 × 1.2 m and 0.75 × 1 m, respectively. As presented in Table 2, for the uniformity calculated by min illuminance / average illuminance or min illuminance /max illuminance, the lighting layout referring to 150lx-standard has the highest final value, while other two solutions have similar values. Given the fact that the whole lighting studied here was a special system (e.g. daylight source plus artificial lighting luminaire), the uniformity was given as the reference for the lighting condition in this office.

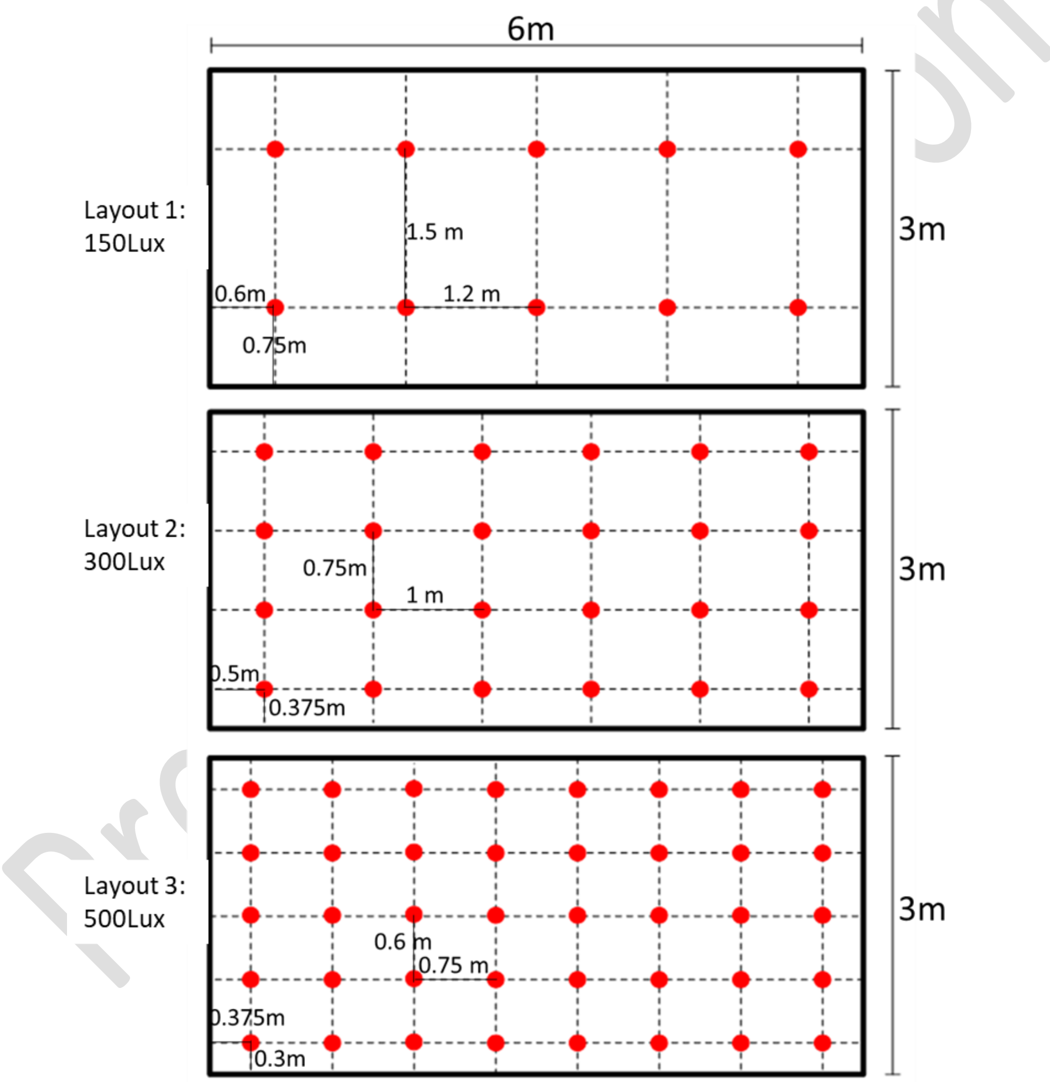

Figure 9. Lighting layouts in the single office with three different illuminance levels.

Table 2. Final calculation results of three lighting layouts using DIALux.

Target illuminance (E_{re})	**Calculated illuminance (E_{av})**	**Uniformity (min/average)**	**Uniformity (min/max)**
150lx	160.0	0.46	0.34
300lx	362.2	0.40	0.29
500lx	599.6	0.40	0.29

3.3 Indoor lighting performances of FODS: visual aspects

This section presents annual variations of indoor lighting levels, with three lighting layouts (Figure 9), the luminaire (Figure 5), and the FODS as a dynamic light source (Figure 2). Two types of lighting levels were assessed, including average horizontal illuminances at the workplane and vertical illuminances at four typical sitting positions (as shown by Figure 3).

3.3.1 Horizontal illuminances at the workplane

This section was used to show if the FODS can provide with proper lighting conditions at the horizontal workplane, which was broadly applied in all building regulations. Figure 10 shows variations of monthly hourly-averaged horizontal illuminance at the workplan in this office with three various lighting layouts (1. 2 and 3). In respect to the monthly luminous flux (Figure 6), the monthly horizontal illuminances varied in a similar trend. Generally, the summer period (July – August) received much higher illuminance levels than the winter period (November – January), while the spring period (March – May) has lower values than autumn (September – October). Compared with May and July, June has lower illuminance levels, and has a flat varying trend of illuminance across the day. For most times of 11 months, the horizontal illuminances were found higher than the three target illuminances (150 lx, 300 lx and 500 lx). However, the winter period (including November, December, and January) failed to meet the target illuminance requirements before 9:00 and after 15:00. Apparently, it was found that all the three lighting solutions with the FODS could be used to provide sufficient light for the workplane at most time in this office. It could be noted that August can deliver very high illuminances than the other months with all lighting layouts. For example, with the layout of target illuminance 150lx, the horizontal illuminance can even achieve the level higher than 400 lx from 9:00 to 15:00. In addition, other two layouts can see a very higher illuminance in August (e.g. > 1000 lx or 2000 lx). This might indicate that the application of FODS system could possibly bring in glare problems in summer.

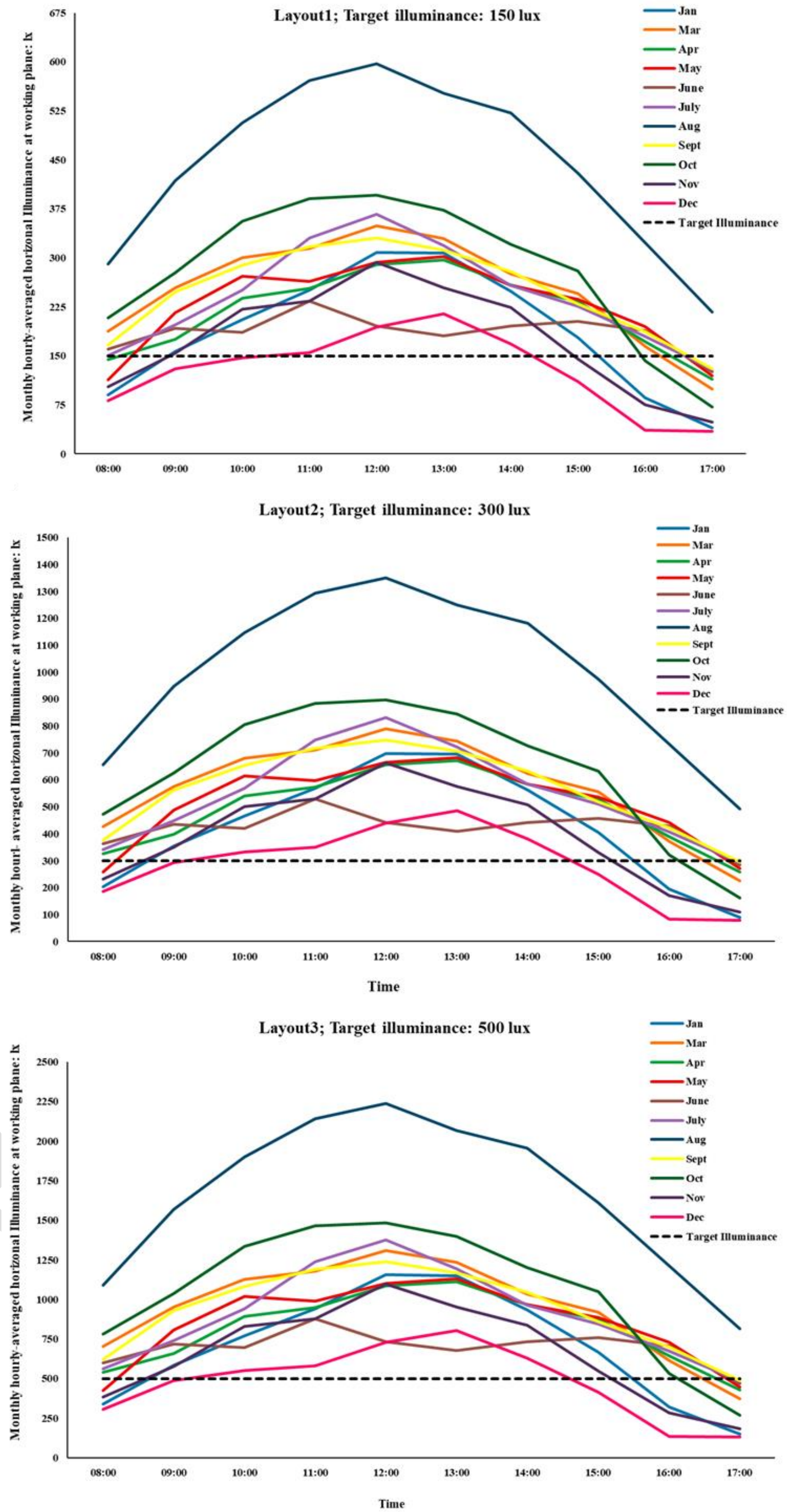

Figure 10. Variations of average horizontal illuminance at the workplan (three lighting layouts).

3.3.2 Vertical illuminances at four typical positions

As mentioned in section 2.3.1 and Figure 3, four typical positions (A1 – 4) were studied based on the lighting levels at the vertical planes of eight observation positions.

First, for the position of A1, variations of monthly hourly-averaged vertical illuminance were displayed in Figure 11 (direction: V1) and Figure 12 (direction: V2). Compared with the horizontal illuminance (Figure 10), similar varying trends of illuminance can be found at the vertical planes, while vertical illuminances at any time were much lower across various times of the year. In fact, for most times, the vertical illuminance can only reach one-fourth of the horizontal illuminance. This might be due to the fact that only the ceiling mounted luminaires were available, even though the light source was daylight. However, for a typical daylit space with side windows, vertical illuminances were normally higher than horizontal illuminances at the workplane. In addition, it can be noted that the facing direction in this room will not take significant effect on the varying trend of vertical illuminances. However, facing the direction V2 can achieve slightly higher vertical illuminance than facing the direction V1. Similar to the impact of lighting layout on the horizontal illuminance, the vertical illuminance tended to be higher with the increased number of luminaires. Thus, in general, December can see three ranges of low-level vertical illuminance as 4~10 lx (Layout1), 18~45 lx (Layout2), and 30~80 lx (Layout3). In summer (August), three ranges of high-level vertical illuminance were: 25~38 lx (Layout1), 110~165 lx (Layout2), and 200~285 lx (Layout3).

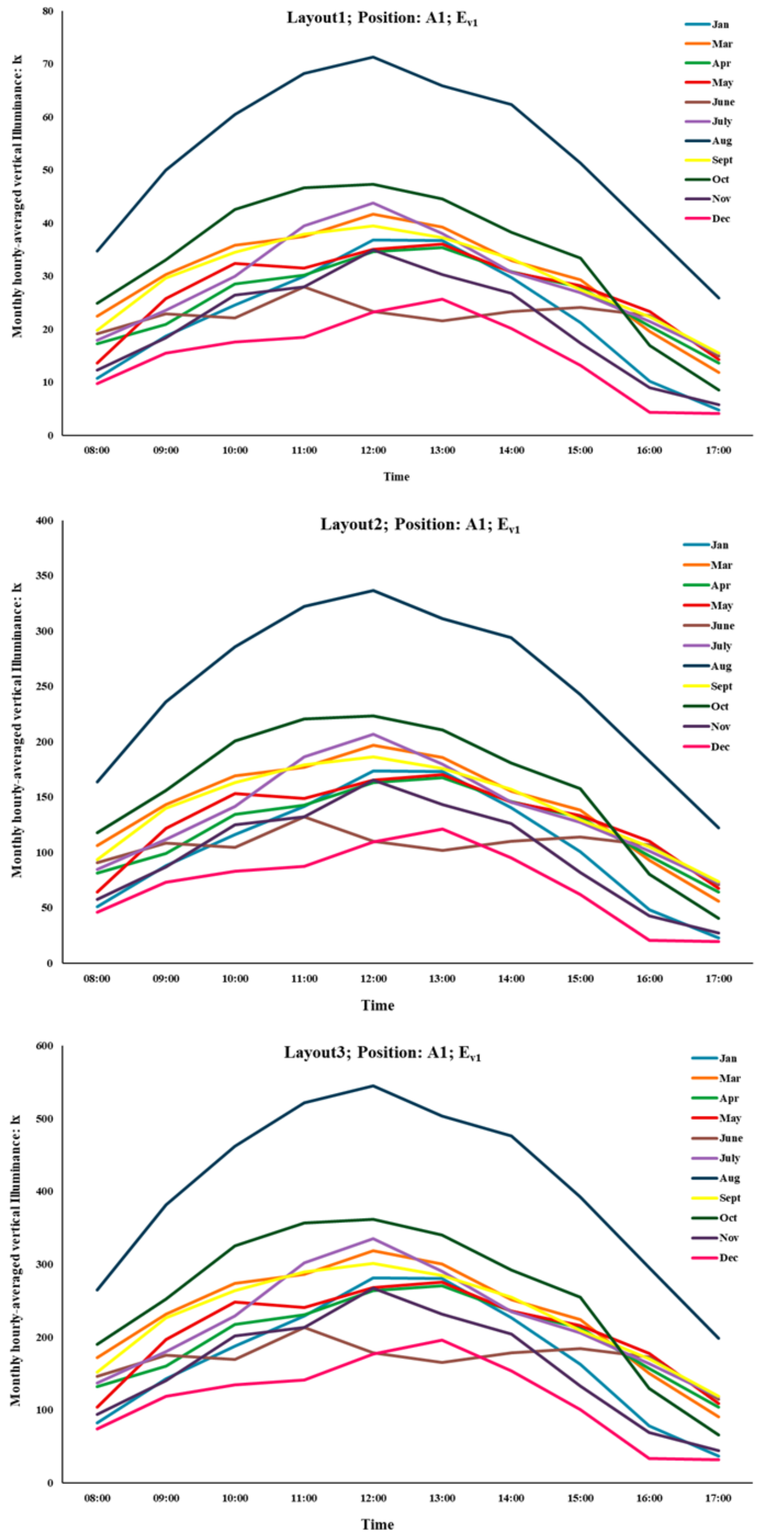

Figure 11. Variations of vertical illuminance at typical sitting positions-A1 (direction: V1) (three lighting layouts).

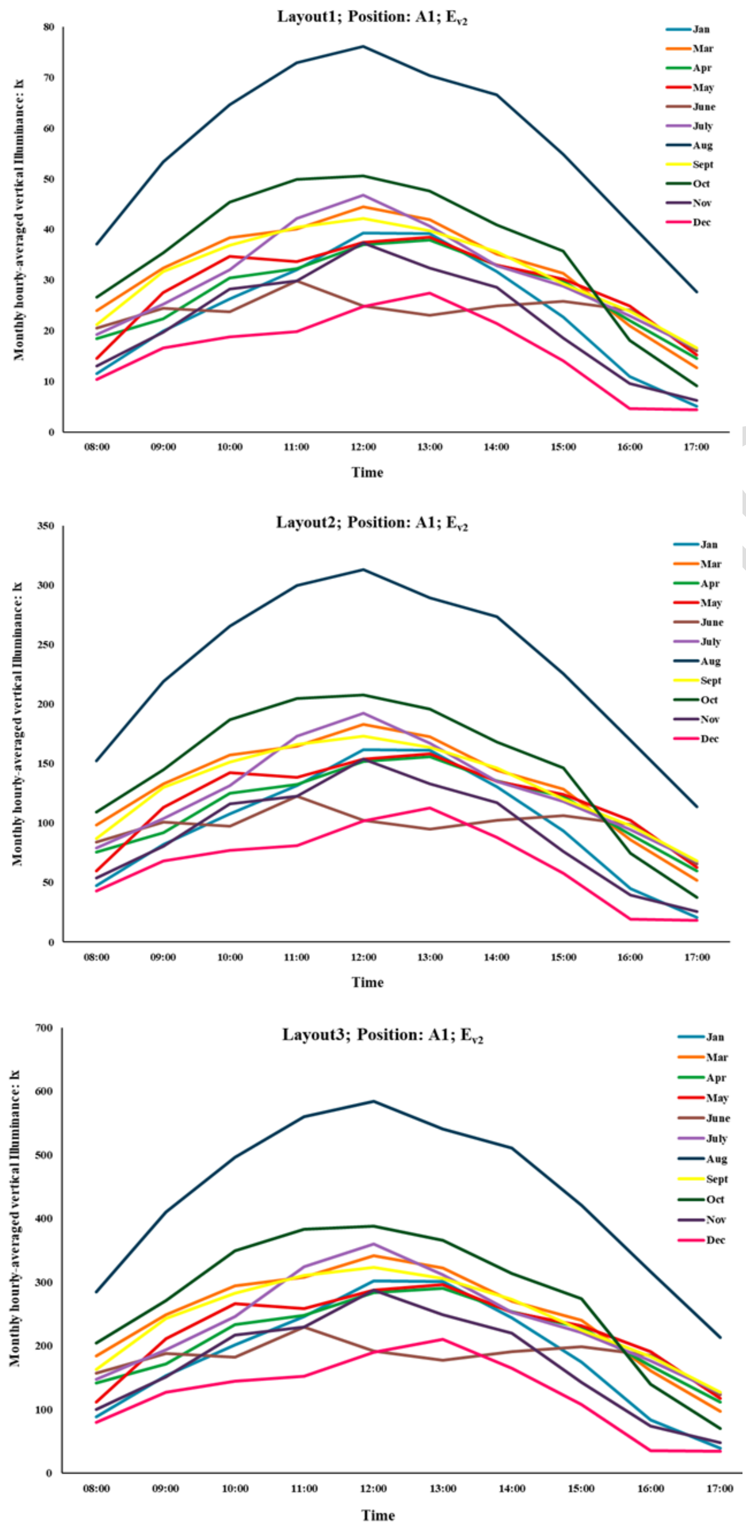

Figure 12. Variations of vertical illuminance at typical sitting positions-A1 (direction: V2) (three lighting layouts).

Second, relative differences (R_p) of monthly hourly-averaged vertical illuminance between A1 and other three positions (A2—4) can be calculated by the following equation:

$$R_P = \frac{E_{v,A(i)} - E_{v,A1}}{E_{v,A1}} \times 100\% \qquad (4),$$

where, $E_{v,A(i)}$ is the monthly hourly-averaged vertical illuminance at other three positions, i= 2, 3, 4; $E_{v,A1}$ is the monthly hourly-averaged vertical illuminance at the position A1. Table 3 presented these relative differences for three positions (A2—4). It can be found that the increasing amount of luminaire would reduce the difference of vertical illuminance between various positions. With the layout1, Position A2 has no clear difference of vertical illuminance from the position A1 at two directions, whereas positions A3 and A4 can see significantly higher values than A1. When applying layout 2 & 3, it seems that positions and directions cannot significantly affect the vertical illuminance. This might be explained by the fact that the vertical illuminance might receive benefits from the increased lighting levels at the workplane.

Table 3. Relative differences of vertical illuminances (R_p) between A1 and other positions (A2-4).

		R_p (%)		
		Position: A2	**Position: A3**	**Position: A4**
Layout1	V1	1.82	147.86	147.86
	V2	-3.0	147.0	98.0
Layout2	V1	-9.50	0.45	-8.60
	V2	0.73	10.95	3.65
Layout3	V1	0.14	0.28	0.14
	V2	1.17	0.26	0.78

3.4 Indoor lighting performances of FODS: circadian stimulus

In this study, CS values were calculated at the four typical positions and two different viewing directions (see Figure 3), taking into account the measured spectral distribution of daylight (section 2.2) and the calculated vertical illuminance (section 3.3.2). Therefore, eight types of CS value (observation positions) were achieved to indicate the circadian performance of FODS applied in this office. Defined as the percentage of the working year when CS exceeds one specific value, cumulative frequency distribution of CS (value: 0~1) was adopted for the data analysis. When CS $\geq$ 0.3, a higher value of such frequency indicated that there is a higher possibility for this FODS to provide with daylight to achieve entrainment of human circadian system.

Figure 13 gives variations of cumulative frequency distribution of CS frequencies in terms of CS range of [0 0.7] and three lighting solutions (Layout 1-3). For the layout 1, the maxima of CS through the working year was around 0.42. In the CS range of [0.3 0.42], all the positions can see that cumulative frequencies were less than 20%, indicating a low possibility to deliver circadian light. In addition, only four observation positions can produce a CS value larger than 0.3, such as A3-V1, A3-V2, A4-V1, and A4-V2. Their cumulative frequencies with CS = 0.3 were 15.6%, 17.9%, 15.6%, and 10.9% respectively. However, other four observation points have CS values less than 0.25. These results can well response to the trend in Table 3. It seems that the layout 1 was not able to provide with proper circadian light for occupants. With regard to the layout 2, the top line of CS has been increased to 0.53. For these observation positions including A1-V1, A1-V2, A2-V1, A2-V2, A3-V1, and A4-V1, cumulative frequencies of CS = 0.3 were between 36% and 40%, which means proper levels of circadian light can be achieved over one-third working year at these positions. On the other hand, observation positions A3-V1 and A4-V2 can only have around 20% working year to get proper levels of circadian light. The application of this lighting layout would clearly increase the possibility to apply the circadian light. As for the layout 3, the CS value can achieve the maxima of 0.6, which indicates a large possibility relating to the use of circadian light. Moreover, cumulative frequencies at CS = 0.3 were approaching 60% for all eight observation positions. For CS $\geq$ 0.5, cumulative frequencies can even achieve 16% to 20%. In general, no clear differences of cumulative frequency variation can be found between eight positions.

As expected, the increased horizontal illuminances at the workplane will significantly increase cumulative frequencies with CS = 0.3 and the maximum CS values at the typical positions. Specifically, cumulative frequency rises from less than 20% with layout 1 to 40% with layout 2, and then achieve around 60% with layout 3, whilst the maximum values of CS are found as 0.42, 0.52 and 0.6 for layouts 1-3 respectively. Differences of circadian light performance between various positions tend to lower as the horizontal illuminance increases. This could be due to the fact that the higher horizontal illuminance would lead to a higher vertical illuminance in this space. However, it could be noted that circadian lights performance at different observation positions is associated with the design of lighting solutions and relevant illuminance standard at the workplane.

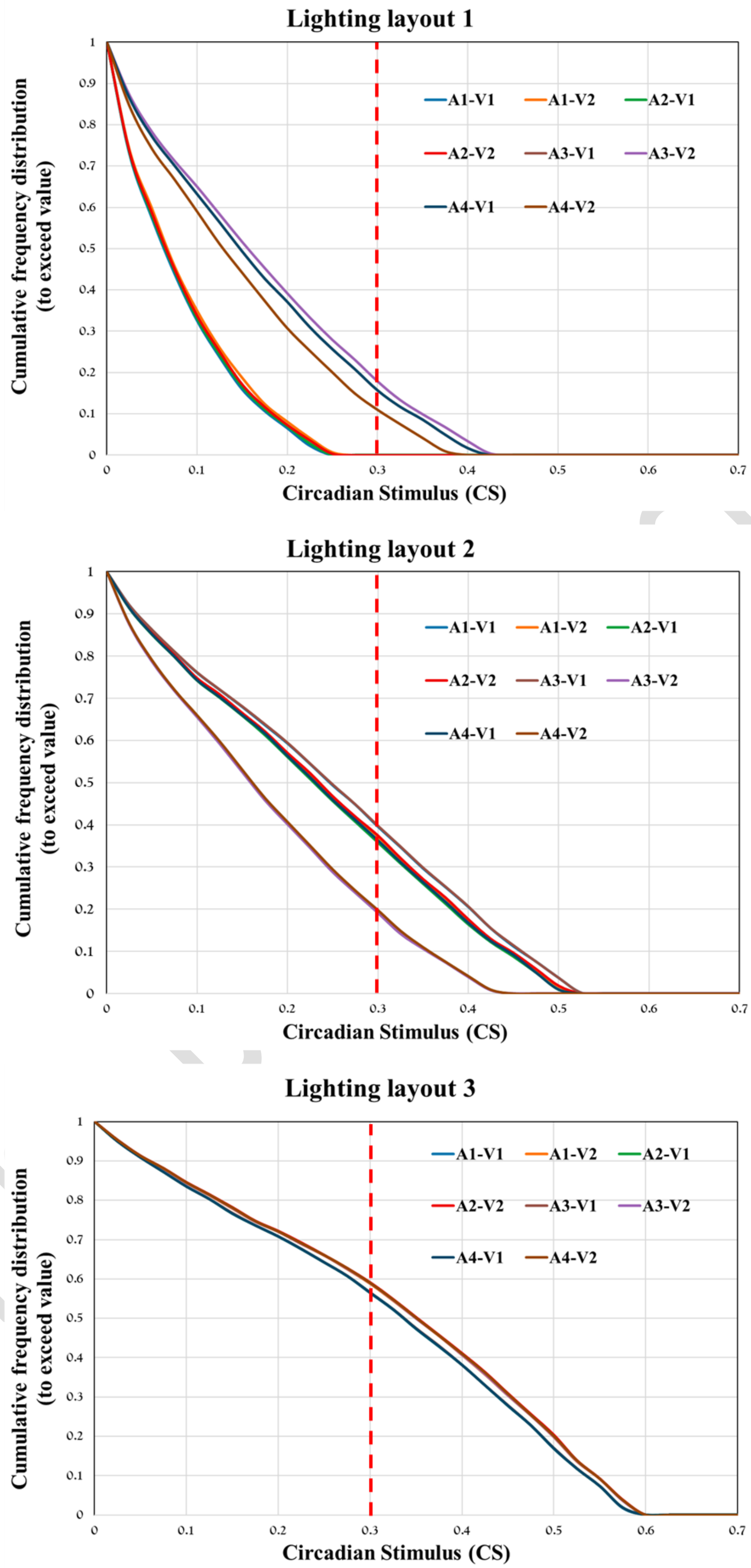

Figure 13. Cumulative frequency distributions of Circadian Stimulus (CS) at four typical positions with three different lighting solutions.

4. Discussion

4.1 Discussion on main results

First, as presented in section 3.4, the metric of CS ≥ 0.3 [35] has helped to expose that this FODS can deliver effective circadian light over 40% of working year. This could indicate that a proper level of circadian light at a windowless workspace could be achieved through applying the FODS in an urban area dominated by climates of northern China (with annual sunshine time of around 2700 hours). According to a European study in an office with side windows [5], the daylight availability has been well identified as an efficient indicator of occupants' satisfaction on basis of both visual and non-visual functions among office workers. Our study has preliminarily exposed the possibility to achieve well non-visual performance in a windowless space. Thus, the benefit of light guide system (e.g. fibre optics daylight system) would be expanded from transferring daylight [14, 15] to delivering effective circadian light.

Second, results from sections 3.3 & 3.4 show that a high level of non-visual effect of lighting (circadian system entrainment) can be reached when a standard lighting requirement was met at the horizontal workplane based on occupants' visual performance. In this single office, the lighting solutions planned based on standard horizontal illuminances at the workplane (e.g. 300 lx and 500 lx) were proved as effective to deliver enough circadian light at the vertical planes (section 3.4). In a normal daylit environment with a higher level of daylight availability via side windows [5-7, 9-10], it can be found that the achievement of proper levels of circadian light would not be difficult. However, there might be not easy to achieve a good balance between visual comfort and non-visual performance due to the direct daylight from side windows [5, 9]. Thus, artificial lighting systems would have to be applied to avoid the default of uncontrollable daylight [3, 5, 35]. On the other hand, light guide systems (e.g. FODS) could be more useful according to this issue, since they can deliver the daylight and effectively distribute it to the space using the same way as artificial lighting systems [14-17].

Third, compared with typical artificial lighting systems, the FODS can deliver circadian light in a more efficient way to the space without any opportunities to open windows and skylights. As shown in section 3.2, the lighting layout designed based on a low horizontal illuminance (150 lx) will deliver an average annual vertical illuminance of 25.73 lx, which can give rise to an average CS of 0.12 (section 3.4). It would be interesting to produce a CS comparison between this daylighting condition delivered by the FODS and typical artificial lighting systems. According to theories of circadian light [37, 38], a simple Circadian Stimulus Calculator was produced by the Lighting Research Centre [44]. Table 4 presents the calculated CS values of five artificial light sources at the same illuminance level (25.73 lx) and their relative differences (with the CS value 0.12 of FODS as a reference). It can be found except for the Blue LED (470nm peak), other four normal light sources can achieve CS values lower than the value of FODS. This could again enhance the benefit of the light guide systems (e.g. fibre optics daylight system).

Table 4. Circadian Stimulus (CS) of five artificial light sources at 25.73 lx (calculated through the tool [44]).

Light source	**CS**	**Relative differences (reference: CS of FODS)**
LED 6500 K Cree XPG cool white	0.044	-63%
Navy 13000K F20	0.086	-28%
Blue LED 470 nm peak	0.371	209%
Philips Mastercolor CDM 100W	0.026	-78%
Promolux F40	0.043	-64%

Finally, this study has exposed the necessity to improve current lighting codes and regulations, which focus on the requirement of various visual functions (as presented in section 3.2). However, design positions relevant to the non-visual performance of lighting, i.e. vertical planes, were not considered in all Chinese building regulations [40, 43]. In addition, the application of light guide systems (e.g. FODS) would possibly make this issue more complicated since their visual and non-visual performances are significantly different from both artificial lighting and traditional daylighting systems. Thus, to produce special guidelines for such fibre optics daylighting systems could be very useful with the advent of a new trend of designing healthy lighting in buildings [3].

4.2 Limitations and future work

Some limitations can be found from this study. First, given the fact that the view to external environment is a critical factor influencing occupants' non-visual performance [4], the FODS might receive less occupants' acceptance than a normal window. Second, the FODS will have to be applied with a special luminaire for indoor lighting (see Figure 5), which would apparently limit its applications. According to the section 3.2, due to its Light Intensity Distribution (narrow beam), this luminaire will deliver a lighting solution requiring for more luminaires than a normal artificial office luminaire (e.g. square light panel, or linear light fixture). In addition, it could be hard to balance the illuminance levels at horizontal and vertical planes and uniformity using this luminaire. Third, based on the structural limitation of luminaire above, the whole cost of this FODS system would be higher than a normal artificial lighting system, even though the former has significant benefit for occupants' health and wellbeing. Last, this FODS was tested under a specific location in north China and some unknown problems might occur when applying it in a different climate.

Future work: A new challenge for expanding application of this FODS will be the improvement of photometric properties of its indoor luminaire. A properly designed luminaire reflector (proper Light Intensity Distribution) might be able to enhance its lighting performance in terms of visual and non-visual functions. In addition, it is expected to conduct a human experiment in a real office with this system to check its performance through subjective assessment.

5. Conclusion

In this study, the potential of one FODS (Fibre Optics Daylighting System) to provide occupants with proper lighting to support visual functions and achieve circadian system entrainment in a single office was assessed through the analysis of monitored data and simulations. Several key findings can be drawn as follows: A proper level of circadian light at a windowless workspace could be achieved via applying the FODS in a climate of northern China. When applying this FODS to meet the standard lighting requirement at the horizontal workplane based on occupants' visual performance in this office, the non-visual effect of lighting (circadian system entrainment) can be attained at the same time. Compared with typical artificial lighting systems, the FODS can deliver circadian light in a more efficient way due to the use of daylight. In general, the application of this FODS system would benefit office workers in terms of both visual and non-visual aspects. This study first investigated the non-visual performance of a fibre optics daylighting system at a workspace.

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References

[1] Galasiu, A.D. & Veitch, J.A., 2006. Occupant preferences and satisfaction with the luminous environment and control systems in daylit offices: a literature review. Energy and Buildings. 38 (7), 728-742.

[2] Aries, M.B.C., Aarts, M.P.J, van Hoof, J., 2015. Daylight and health: A review of the evidence and consequences for the built environment. Lighting Research & Technology. 47, 6-27.

[3] Khademagha, P., Aries, M.B.C., Rosemann, A.L.P., Loenen, E.J., 2016. Implementing non-image-forming effects of light in the built environment: a review on what we need. Building and Environment. 108, 263-272.

[4] Aries, M. B. C., Veitch, J. A and Newsham, G. R, 2010. Windows, view, and office characteristics predict physical and psychological discomfort. Environmental Psychology. 30, 533-41.

[5] Borisuit, A., Linhart, F., Scartezzini, J-L., Munch, M., 2015. Effects of realistic office daylighting and electric lighting conditions on visual comfort, alertness and mood. Lighting Research & Technology. 47, 1-18.

[6] Boubekri, M., Cheung, I.N., Reid, K.J., Wang, C.H., Zee, P.C., 2014. Impact of windows and daylight exposure on overall health and sleep quality of office workers: a case-control pilot study. Journal of Clinical Sleep Medicine. 10(6), 603-611.

[7] Figueiro, M. G., Rea, M. S. 2016. Office lighting and personal light exposures in two seasons: Impact on sleep and mood. Lighting Research & Technology, 48(3), 352-364.

[8] Figueiro, M. G., Steverson, B.C., Heerwagen, J., Kampschroer, K., Hunter, C.M., Gonzales, K., Plitnick, B. 2017. The impact of daytime light exposures on sleep and mood in office workers. Sleep Health, 3(3), 204-215.

[9] Chen, X., Zhang, X., Du, J., 2019. Exploring the effects of daylight and glazing types on self-reported satisfactions and performances: a pilot investigation in an office. Architectural Science Review. 64(4), 388-352.

[10] Chen, X., Zhang, X., Du, J., 2019. Glazing type (colour and transmittance), daylighting, and human performances at a workspace: A full-scale experiment in Beijing. Building and Environment. 153, 168-185.

[11] Kischkoweit-Lopin, M., 2002. An overview of daylighting systems. Solar Energy, 73(2), 77-82.

[12] Littlefair P.J, 1990. Innovative daylighting: review of systems and evaluation method. Lighting Research and Technology, 22(1), 1-17.

[13] IEA (SHC Task 21/ ECBCS Annex 29), 2000. Daylight in buildings: a source book on daylighting system and components. Report of Lawrence Berkeley National Laboratory. Available from: https://facades.lbl.gov/daylight-buildings-source-book-daylighting-systems [Accessed 10 July 2016].

[14] Kim, J. T., & Kim, G., 2010. Overview and new developments in optical daylighting systems for building a healthy indoor environment. Building & Environment, 45(2), 256-269.

[15] Mayhoub M.S., 2014. Innovative daylighting systems' challenges: A critical study. Energy and Buildings, 80(80), 394–405.

[16] Whang, J. W., Chen, Y. Y., & Wu, B. Y., 2009. Innovative design of cassegrain solar concentrator system for indoor illumination utilizing chromatic aberration to filter out ultraviolet and infrared in sunlight. Solar Energy, 83(8), 1115-1122.

[17] Wang, C., Abdul-Rahman, H., & Rao, S. P., 2010. Daylighting can be fluorescent: development of a fibre solar concentrator and test for its indoor illumination. Energy and Buildings, 42(5), 717-727.

[18] Han, H., & Kim, J. T., 2010. Application of high-density daylight for indoor illumination. Energy, 35(6), 2654-2666.

[19] Xue, X., Zheng, H., Su, Y., & Kang, H., 2011. Study of a novel sunlight concentrating and optical fibre guiding system. Solar Energy, 85(7), 1364-1370.

[20] Han, H. J., Riffat, S. B., Lim, S. H., & Oh, S. J., 2013. Fibre optic solar lighting: functional competitiveness and potential. Solar Energy, 94(4), 86-101.

[21] Ullah, I., & Shin, S., 2014. Highly concentrated optical fibre-based daylighting systems for multi-floor office buildings. Energy & Buildings, 72(2), 246-261.

[22] Song, J., Zhu, Y., Jin, Z., & Yang, Y., 2014. Daylighting system via fibres based on two-stage sun-tracking model. Solar Energy, 108, 331-339.

[23] Song, J., Jin, Z., Zhu, Y., Zhou, Z., & Yang, Y., 2015. Development of a fibre daylighting system based on the parallel mechanism and direct focus detection. Solar Energy, 115, 484-493.

[24] Lim, H. C. , Kim, H. , Jang, K. , Kim, J. Y. , Baek, J. H. , & Yang, S. J. , et al, 2015. Design and fabrication of light-guiding plate for a photobioreactor that utilizes sunlight. Optical Review, 22(5), 779-785.

[25] Vu, N. H., & Shin, S.,2016. Cost-effective optical fibre daylighting system using modified compound parabolic concentrators. Solar Energy, 136, 145-152.

[26] Song, J., Zhu, Y., Tong, K., Yang, Y., & Reyes-Belmonte, M. A., 2016. A note on the optic characteristics of daylighting system via pmma fibres. Solar Energy, 136, 32-34.

[27] Muhammad A. C. M., Karam M. A., Mohd R. I., and Abdul M. A. R., 2016. Potential of fibre optic daylighting systems in tropical Malaysia. Indoor and Built Environment, 25(3), 466–480.

[28] Ullah, I., Lv, H., Whang, J. W., & Su, Y., 2017. Analysis of a novel design of uniformly illumination for fresnel lens-based optical fibre daylighting system. Energy and Buildings, 154, 19-29.

[29] Ravi G., Meg T., Sean L., 2017. Design and development of a faceted secondary concentrator for a fibreoptic hybrid solar lighting system. Solar Energy, 157, 629-640.

[30] Sedki, L., & Maaroufi, M., 2017. Design of parabolic solar daylighting systems based on fibre optic wires: a new heat filtering device. Energy and Buildings, 152, 434-441.

[31] Thanh T. P., Vu, N. H, and Shin S., 2017. Daylighting System Based on Novel Design of Linear Fresnel lens. Buildings, 7, 92;

[32] Barbón, A., Sánchez-Rodríguez, J.A., Bayón, L., & Barbón, N., 2018. Development of a fibre daylighting system based on a small scale linear Fresnel reflector: theoretical elements. Applied Energy, 212, 733-745.

[33] Barbón A., Pardellas A., Fernández-Rubiera J.A., Barbón N., 2019. New daylight fluctuation control in an optical fibre-based daylighting system. Building and Environment, 153,35–45.

[34] International WELL Building Institute, 2018. WELL building Standard (v2). www.wellcertified.com (final access: 01/06/2019).

[35] Figueiro, M. G., Kalsher, M., Steverson, B.C., Heerwagen, J., Kampschroer, K., Rea, M.S. 2019. Circadian-effective light and its impact on alertness in office workers. Lighting Research & Technology, 51, 171-183.

[36] Arsenault, H., Hébert, Marc., Bubois, M-C. 2012. Effects of glazing colour type on perception of daylight quality, arousal, and switch-on patterns of electric light in office rooms. Building and Environment. 56, 223-231.

[37] Rea, M. S., Figueiro, M.G., Bierman, A., Hamner, R. 2012. Modelling the spectral sensitivity of the human circadian system. Lighting Research and Technology, 44: 386–396.

[38] Rea, M. S. and Figueiro, M. G. 2018. Light as a circadian stimulus for architectural lighting. Lighting Research and Technology. 50(4): 497-510.

[39] JGJ 67, 2006, Design code for office building, China: Ministry of Housing and Urban-Rural Development.

[40] GB/T 50034, 2013, Standard for lighting design of buildings, China: Ministry of Housing and Urban-Rural Development.

[41] Muneer, T, 2004, Solar Radiation and Daylight Models. Publisher: Elsevier Butterworth-Heinemann, UK.

[42] Janjai, S. , Pattarapanitchai, S., Prathumsit, J., Buntoung, S., Wattan, R., Masiri, I. A method for mapping monthly average hourly diffuse illuminance from satellite data in Thailand. Solar Energy 2014; 102: 162-172.

[43] GB/T 50033, 2013, Standard for daylight design of buildings, China: Ministry of Housing and Urban-Rural Development.

[44] Lighting Research Centre. 2017. Circadian stimulus calculator. https://www.lrc.rpi.edu/cscalculator. (final access: 01/06/2019).