Journal Pre-proof


# Exploring the environmental performance of liquid glass coating using Sol-Gel technology and responsive Venetian blinds in the tropics

Karam M. Al-Obaidi, Husam S. Al-Duais, Nayef A.M. Alduais, Ali Alashwal, Muhammad Azzam Ismail

PII: S2352-7102(22)01335-3

DOI: https://doi.org/10.1016/j.jobe.2022.105329

Reference: JOBE 105329

To appear in: *Journal of Building Engineering*

Received Date: 17 July 2022

Revised Date: 22 September 2022

Accepted Date: 25 September 2022

Please cite this article as: K.M. Al-Obaidi, H.S. Al-Duais, N.A.M. Alduais, A. Alashwal, M.A. Ismail, Exploring the environmental performance of liquid glass coating using Sol-Gel technology and responsive Venetian blinds in the tropics, *Journal of Building Engineering* (2022), doi: https://doi.org/10.1016/j.jobe.2022.105329.

# Exploring the environmental performance of liquid glass coating using Sol-Gel technology and responsive Venetian blinds in the tropics

Karam M. Al-Obaidi [1,*], Husam S. Al-Duais [2], Nayef A.M. Alduais [3] , Ali Alashwal [4] and Muhammad Azzam Ismail [2]

[1] Department of the Natural and Built Environment, College of Social Sciences and Arts, Sheffield Hallam University, Sheffield, UK

[2] Department of Architecture, Faculty of Built Environment, Universiti Malaya, Kuala Lumpur, Malaysia

[3] Faculty of Computer Science and Information Technology, Universiti Tun Hussein Onn Malaysia, Johor, Malaysia

[4] School of Engineering, Design and Built Environment, Western Sydney University, Australia

*Corresponding author: Karam M. Al-Obaidi (E-mail: k.al-obaidi@shu.ac.uk)

## Abstract

The dynamic nature of tropical skies presents challenges for the built environment due to the momentous fluctuations and instability in solar irradiance and illuminance levels that cause limitations in responding to the needs of the indoor environment. The study aims to investigate the performance of daylighting strategies using liquid glass coating and responsive Venetian blinds in an office building in the tropics. The objective of this study is to systematically examine the impacts of proposed strategies on indoor environmental conditions. The study was experimentally investigated by utilising field measurements in full-scale cellular offices in a real environment and simulation using Radiance. The results indicated that responsive Venetian blinds provided steady daylight levels between 375 lx and 588 lx in the centre of the room, while a further integration with liquid glass coating provided a glare control with a maximum of 33.71 % (Imperceptible) using Daylight Glare Probability. The indoor air temperature was reduced by 3.42 °C with liquid glass coating and 2.85 °C with responsive Venetian blinds. The outputs of assessing the performance of static and responsive strategies demonstrated new findings that are significant to developing these strategies in the tropics.

**Keywords:** daylight performance; indoor thermal conditions; liquid glass coating; responsive blinds; office buildings; tropics

## 1. Introduction

Building envelope plays an important role as a controller of daylight admission and a thermal regulator via its transparent components to provide a comfortable indoor environment (Davila and Fiorito, 2021). Recent studies of daylighting in the tropics conducted by Lim and Heng (2016), Lim et al. (2017), Al-Masrani et al. (2018), Kwong (2020) and Bahdad et al. (2021 & 2022) indicated critical issues in terms of daylight levels and thermal conditions in office buildings. Al-Masrani et al. (2018) performed an analysis of weather data by assessing solar irradiance in tropical cities. The study found that tropical skies with their dynamic changes demonstrate instability in outdoor illuminance that causes limitations in the development of daylighting systems. This challenge also causes variability in illuminance levels that would affect indoor environments (Chirarattananon et al., 2003; Al-Obaidi et al., 2017). The challenges with tropical skies extend to the cloud occurrence frequency that alters within minutes which affects direct solar irradiance due to irregularity in sky patterns (Tang and Chin, 2013). Al-Masrani et al. (2018) reviewed the performance of daylight and thermal aspects of office buildings in the tropics, the examination showed some limitations due to the sensitivity of illuminance behaviour in such regions.

Common strategies for controlling light transmission in buildings include external shadings, blinds, louvres and glazing modifications such as films, coating and insertions (Huang et al., 2013; Mayhoub, 2014). The development of window systems has been explored from various perspectives that cover design characteristics, materials, integrations and combinations of different daylighting techniques.

Glass coating materials such as solar films are used to enhance the properties of glass windows and façades. In hot areas, coating materials are utilised to reduce solar access and control visible light transmission which would help to save a considerable amount of energy. Somasundaram et al. (2020) experimented with the installation of a solar film in an existing building with a Low-E coating internal glass in Singapore. The solar film has 18.5 % total solar energy transmission, 10 % solar energy reflection, 71.5 % solar energy absorbed, 35 % visible light transmission, and 99 % ultraviolet reflection. However, the study found that lighting and HVAC may have opposing requirements in terms of the transmissivity of the glass. Cannavale et al. (2020), Lee et al. (2020) and Day et al. (2019) investigated electrochromic glazing (EC), they stated that EC glass in buildings is a useful strategy for glare control, only if it is utilised in the right context. Tian et al. (2019 & 2020) investigated daylight redirecting film (DRF) applied onto an upper window that can improve daylight uniformity and enhance daylight levels in deep spaces on clear days. However, this film is only limited to improving light in higher parts of the window and for deep rooms. Do and Chan (2021) found that larger film to wall ratios create issues with glare and heat gain by increasing daylight levels and reducing occupants' outdoor views. Zhao et al. (2022) tested a semi-transparent radiative cooling glass that was conducted experimentally by comparing two small-scale boxes to test light and thermal performance. However, the study was mainly about assessing thermal conditions and cooling loads. Finally, these static applications would help to provide a sufficient indoor environment for a specific period during the year, however, they are inefficient in reacting and performing due to the constant changes in weather conditions (Davila and Fiorito, 2021).

Various studies such as Lim and Heng (2016) and Huo et al. (2021) indicated that external shadings could be more efficient compared to utilising internal shadings in preventing heat gain from sunlight. Nevertheless, internal shadings provide effective strategies for controlling daylight and glare and offering the preferred visual environments (Lim and Heng, 2016; Kim et al., 2018). Several studies investigated the practicality of Venetian blinds that demonstrated an improved environment such as Olbina and Hu (2012) who assessed the performance of daylight and thermal conditions using automated split-controlled blinds. However, the study was limited to the use of UDI designed daylight levels (500-2000 lx) and indicated that direct sunlight could lead to discomfort glare when illuminance levels are higher than 2000 lx. Day et al. (2019) tested automated Venetian blinds to assess occupants' subjective visual comfort perceptions in the USA. Though, the results mainly discussed the impact of physical measurements and survey results from users' perceptions. Luo et al. (2020) investigated daylight that is linked with shading strategies for automated blinds using Radial Basis Function (RBF) optimization in China. However, the study was limited in controlling light levels on workplane areas between 500 lx and 1000 lx and provided no more than 35 % of examined space in a satisfactory condition with useful illuminance thresholds. Kunwar et al. (2020) also stated that many publications discussed simulation-based studies that are yet to be tested using full-scale experiments. The study summarises studies on dynamic shading systems and their methods and application in office buildings as shown in Table 1.

Table 1: Summary of recent studies on dynamic shading systems in office buildings.

| | Studies | Research parameters | Methods | Building | System | Location |
|---|---|---|---|---|---|---|
| **1** | Wu and Zhang (2022) | daylighting and energy performance of a complex, dynamic, origami-based shading system | simulation and validated by experimental data | office building | performance-based design of complex dynamic shading | China |
| **2** | Tabadkani et al. (2021) | automatic shading control functions, user comfort and energy load | algorithm & simulation | office space | shading control scenarios | Australia, Egypt, Singapore, UK, India, Germany, Canada, Iran, and Chile |
| **3** | Xie and Sawyer (2021) | annual glare analysis, lighting energy use and view access | simulation and machine learning algorithms | office buildings | glare control with automated shading system | USA |
| **4** | Do and Chan (2021) | daylight availability, glare prevention, and visibilit | simulation | test cell | daylight-redirecting window film and automated roller shade | Taipei, Taiwan |
| **5** | de Vries et al. (2021) | lighting, cooling and heating and energy consumption | simulation | office space | a novel multi-state sun-tracking vertical-blind | Netherlands |
| **6** | Chiesa et al., (2020) | a fuzzy-logic IoT lighting and shading control system | simulation and experement | test cell | smart system in buildings based on sensing and actuating nodes | Italy |
| **7** | Do and Chan (2020) | Incident sunlight, Illuminance, shading status, Continuous daylight autonomy, Daylight glare probability | simulation | office space | combinations of roller shades, blinds, and proper control algorithms | Taiwan & New York |

| | | | | | | |
|---|---|---|---|---|---|---|
| **8** | Luo et al. (2020) | tilting angle and workplane illuminance and glare evaluation | simulation - grasshopper and diva and calculation | office space | model-based shading control for predetermining shading positions | Harbin, China |
| **9** | Al-Masrani et al. (2018) | daylight and thermal performance | review | office buildings | dynamic shading systems | Tropics |
| **10** | Kim et al. (2018) | temperature, illuminance, annual heating/cooling loads and lighting consumption | simulation – EnergyPlus and Daysim | office building | a double skin façade (DSF) system with interior and exterior blinds | South Korea |
| **11** | Al-Obaidi et al. (2017) | illuminance levels | empirical – full scale with plc | full scale test cell | integration of dynamic shading device and fibre optic daylighting system | Malaysia |
| **12** | Iwata et al. (2017) | illuminance, predicted glare sensation vote, view satisfaction, power reduction for lighting and dimming ratio for lighting | calculations and simulation | office space | automated blind control based on glare prevention with dimmable light | Japan |
| **13** | Chaiwiwatworakul and Chirarattananon (2013) | daylight illuminance and energy consumption | experiments and and simulation | laboratory building | double-pane window with enclosed horizontal slats | Thailand |
| **14** | Kazanasmaz (2013) | daylight illuminance | field measurements and simulation | office space | movable blind system | Turkey |
| **15** | Olbina and Hu (2012) | control methods and the daylighting and thermal performance | simulation - EnergyPlus | office space | automated split-controlled blinds | Florida, United States |

Active shading systems are classified into systems that are managed by the user and systems that are automatically performed in response to indoor or outdoor conditions. The advancement in automatic response within specific conditions was examined by several studies (Chiesa et al., 2020; Tabadkani et al., 2021). Dynamic shadings are defined as responsive systems when they automatically respond to the environment by collecting information from their surroundings and performing movements without an agent (Karanouh and Kerber, 2015). Dynamic shading systems function as responsive and interactive systems. They are responsive when reacting to environmental changes without considering user interaction (Kolodziej and Rak, 2013), while they are interactive when performing tasks that take into account environmental changes and user intervention in their functions (Achten, 2011). These systems consist of three components to operate: sensors and network to collect data, a controller to process data and actuators to perform actions (Sharaidin, 2014; Konstantoglou and Tsangrassoulis, 2016; Al-Obaidi et al., 2017; Al-Masrani and Al-Obaidi, 2019).

Al-Masrani and Al-Obaidi (2019) reviewed control strategies in dynamic shading systems, the study revealed two forms of control systems: open-loop (feedforward) and closed-loop (feedback). An open-loop controls any system by directly activating the actuator without using feedback driven by stimuli, such as outdoor illuminance levels (Reinhart and Voss, 2003), the angle of incident sunlight (Mukherjee et al., 2010), or hourly sky conditions (Nezamdoost et al., 2018). A closed-loop system utilises an evaluation method to assess outputs and desired findings as a feedback signal to continually decrease the variation (error) (Hammad et al., 2010). Finally, Al-Masrani et al. (2018) reviewed the optimisation of solar shading systems for office buildings in the tropics and found that mechanical and dynamic shading systems are still under criticism due to cost and energy consumption. The study indicated that movement speed and responsive behaviour in systems remain unclear and require further investigation. Also, the study suggested further considerations in designing shading systems for the tropical built environment.

From examining the literature, the study found no detailed research has been experimentally investigated in applying liquid glass coating using Sol-Gel technology. Also, there are limited studies conducted on responsive Venetian blinds and physical controllers in cellular offices to understand tropical skies in a full-scale model and under a real environment in the tropics. The research found that many studies focused on dynamic Venetian blinds using limited controller technologies. However, tropical sky conditions are noticeably sensitive in experiencing fluctuations in illuminance levels that lead to issues with glare and heat gain that are difficult to control in conventional ways. Also, the investigation noted that many previous studies used simulation, while a minimum number of studies used field measurements with a full-scale model in this research field, especially in the tropics. In addition, the research found limited studies in performing investigations using real comparisons with multiple and identical rooms simultaneously to ensure the accuracy of produced data. Furthermore, the study detected limitations in studying controllers, motion speed and responsive behaviour in the tropics. Therefore, a minimalistic and simple solution that combines different strategies would be more effective in controlling diffused light. As a result, the performance of advanced daylighting strategies requires a systematic investigation in the tropics.

This study aims to investigate the environmental performance of indoor daylight and thermal conditions using liquid glass coating and responsive Venetian blinds in an office building in the tropics. The objective of this study is to systematically examine the impacts of proposed daylighting strategies on the indoor environment to identify their potential and limitation in this region. This research seeks to demonstrate new findings in examining the performance of a responsive method that uses a closed-loop control system known as a feedback system to control light levels between 300 lx and 500 lx and reduce heat gain in the centre of the room in the tropics. Also, an original evaluation of utilising liquid glass coating on large windows for office spaces with a south orientation to decrease heat gain and test daylight conditions. Furthermore, the new contributions are linked to assessing the differences in indoor environmental conditions with different passive and active daylighting technologies in existing offices under tropical conditions. Finally, the study demonstrates a systematic investigation of static and responsive daylighting strategies in the tropics.

## 2. Materials and Methods

This study presents results from full-scale investigations that were conducted by field measurements and simulation using Radiance. The research used a quantitative method based on collected physical data to evaluate indoor environmental conditions by assessing daylight levels, daylight glare probability (DGP) and air temperature. The following sections explain the process and steps for a responsive system, liquid glass coating and test rooms with methods of physical data measurement.

### 2.1 Responsive Venetian Blinds

This study utilised daylighting monitoring protocols by using closed-loop control to operate the Venetian blinds, the control signal modifies the slat angle according to three inputs: daylight set-point, outdoor illuminance and measured workplane illuminance (feedback). The system consists of three main levels: sensing, control and actuator. The system items used in this study are Arduino Uno, Light Sensor (SN-LDR- MD), Servo Motor (MG995 Metal Gear Servo) and Venetian blinds (240cm(W) × 320cm(H) × Slats 50 mm, pulley system – white PVC blinds) as shown in Figure 1(a). The gear design considers an original development in this study which represents the main actuator of the proposed system. Basically, it includes a servo motor, 3D printed motor gear with 18 teeth, 3D printed gear (blinds cord holder) with 36 teeth and 3D printed base as shown in Figure 1(b). Indoor and outdoor light sensors were connected to the microcontroller that controlled the servo motor.

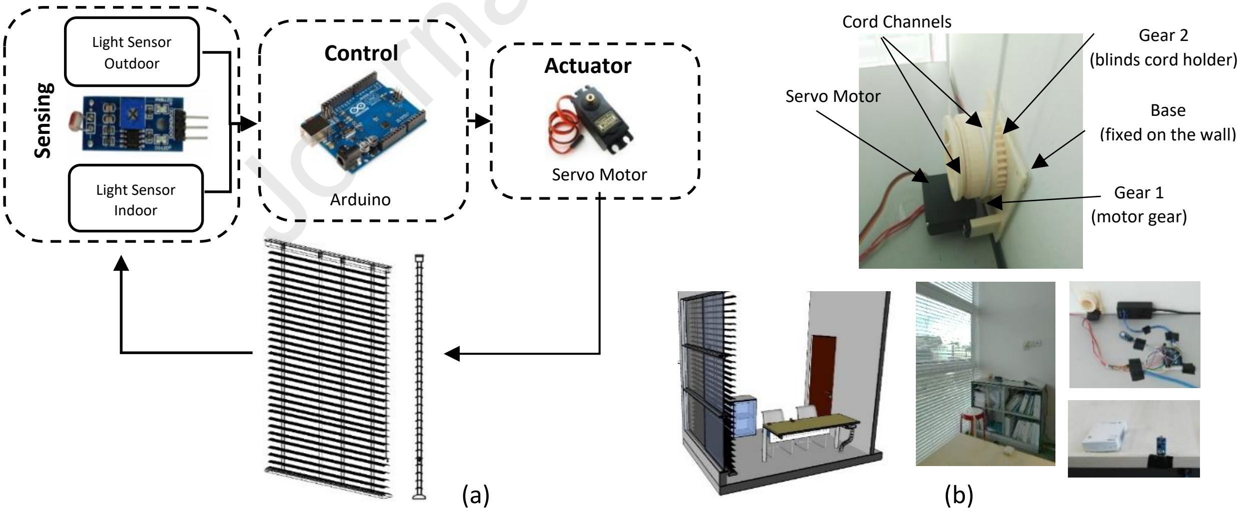



Figure 1: (a) Physical components of the proposed responsive blinds; (b) Actuator components and design.

Two algorithms were proposed to optimize daylight levels in the room. Each algorithm is divided into two phases: the setup phase and the process phase as shown in Figure 2. In the setup phase, following Malaysian standard (MS1525:2017) and CIBSE Guide A (2015) for office space (computer workstation), the proposed system assigned 300 lx and 500 lx for minimum and maximum light intensity, respectively. The research conducted an initial analysis to set direct sunlight identification in the system for Kuala Lumpur. It was found that moving the slat up with a minimum angle of 25° is practical to block direct sunlight during the lowest sun angle on 21 Dec to control glare, further demonstrations are provided in section 2.3. The research used an efficient microcontroller system that uses low energy and provides an instant response to indoor daylight levels. Also, the system used a servo motor to provide a smooth movement between 0 – 90 degrees. For the process phase, the process works via Arduino / sensor board by reading the light intensity of the outdoor via a light sensor. The system optimizes the room light based on the acceptable range as follows, (i) As long as the light in the room is less than the minimum set-point light value, the slats are gradually opened till reach the acceptable range (300 lx - 500 lx). (ii) In the same way, if the room light is greater than the maximum light value, the slats move up 25° and gradually optimize the angles between 25° and 90° till reaching the acceptable range (300 lx - 500 lx). The detailed process is demonstrated in two stages below.

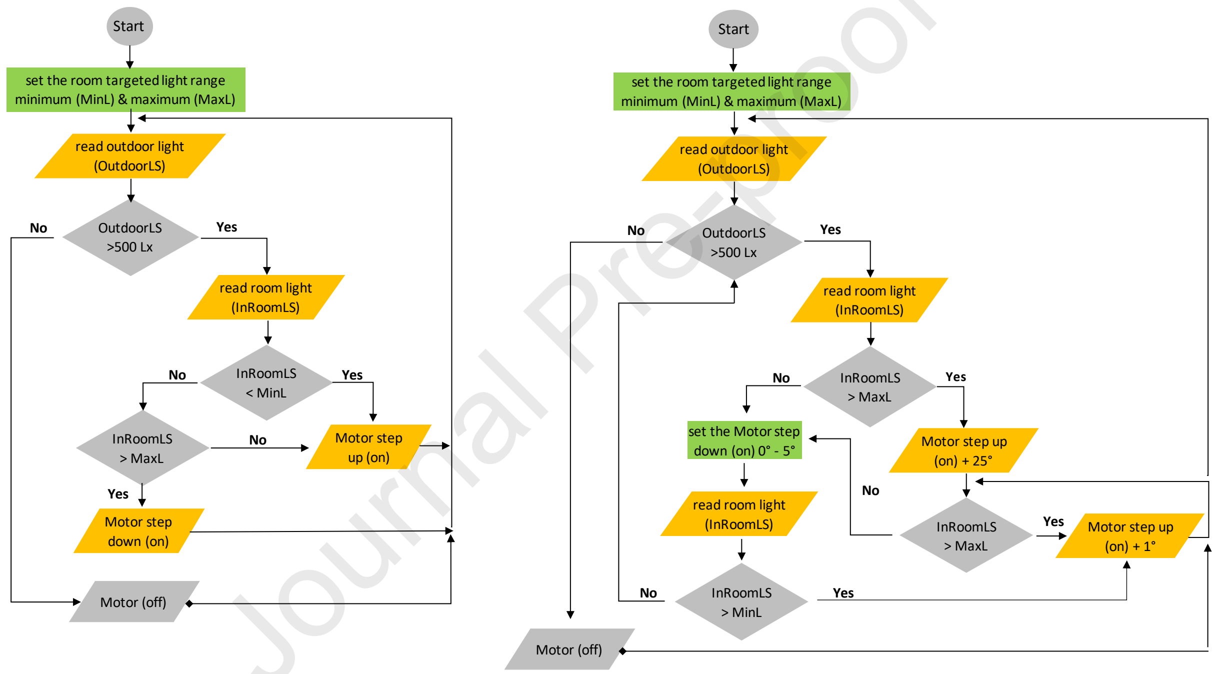



Figure 2: Flowchart of the control process to optimize daylight levels in empirical and simulation processes.

## 2.2 Liquid glass coating using Sol-Gel technology

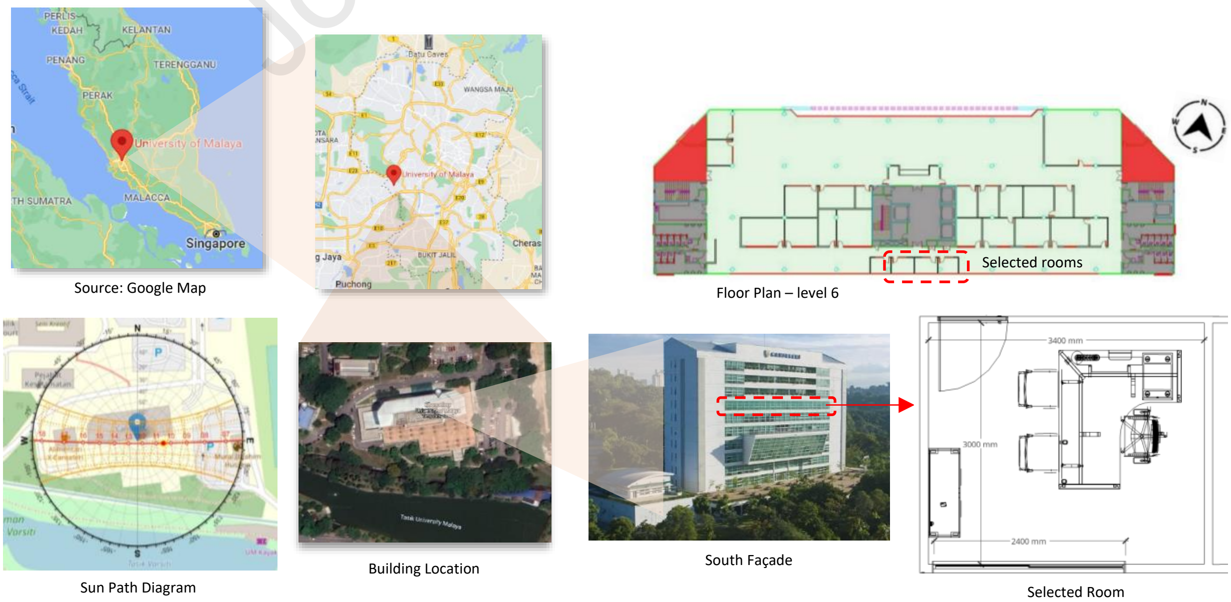
The research targeted a new glass coating that uses nano-sized ingredients of Sol-Gel Technology. The coating is certified by Singapore Green Building Product (SGBP). The glass coating was assessed via a pilot test to evaluate thermal performance in air-conditioned rooms and a glasshouse at the University of Malaya in Malaysia (Kristalbond, 2022). However, the material requires to be tested experimentally in a real office building to assess its daylight performance and thermal conditions in the tropics. The liquid glass coating was sourced from a local company in Malaysia and applied on a large window of 3.2m x 2.4m in one of the test rooms to assess its performance against other rooms. The material consists of Sio2 with cross-linked UV and IR absorber and it is developed to block 99 % of the sun's UVA and UVB and 90 % of the Infrared ray. The coating smooths the surface by filling up micro size pits and unevenness, improving the glass clarity and allowing high visible light transmission of 70 %. The material performs better than most tint films that have a VLT range of 45 % - 20 %. The coating works as absorptive not reflective. It is an ultra-clear nano-coating and reduces reflection on the glass. It is only 6-7 microns thin with a low haze level of 0.8. The material only allows 10 % of Infrared transmittance and has 55 % solar transmission via Spectrum Detective Energy Transmission Meter. The material is suitable for retrofitting on the interior glass surface. However, this coating cannot be applied on Low-E glass or reflective (mirror) glass. Therefore, this material was applied to a window with 6mm clear glass, further details of physical properties are provided in Table 2.

Table 2: Spectral performance data of clear float glass and liquid glass coating.

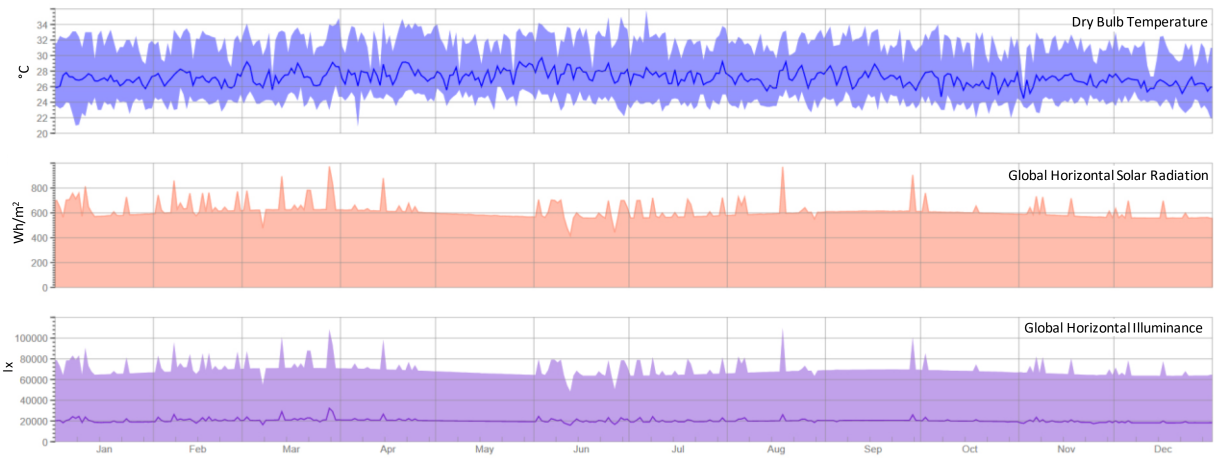
| Product Name | Glass Thickness (mm) | Visible Light (%) | | | Solar Radiation (%) | | | UV Trans (%) | SHGC | Shading Coefficient | U-Value (W/m2K) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Trans | Ref | Abs | Trans | Ref | Abs | | | | |
| **Liquid Glass Coating** | 6 | 70.8 | 10.0 | 19.2 | 34.6 | 8.5 | 56.9 | 0.0 | 0.51 | 0.58 | 3.46 |
| **Clear Float** | 6 | 88.6 | 7.9 | 3.5 | 77.9 | 6.9 | 15.2 | 59.2 | 0.82 | 0.93 | 5.59 |

### 2.3 Test rooms and methods of physical data measurement

Full-scale experimental testing of three different daylighting strategies in three rooms was conducted at an office building in Malaysia. The experiment was performed at 3°07'13.4N latitude, 101°39'25.1"E longitude, the test facility is located at the Chancellery building in the University of Malaya, Kuala Lumpur, Malaysia (Figure 3). The building is approximately aligned with the true north and the main facades are oriented toward the north and the south. Malaysia is a country located in a tropical region with hot, humid and rainy conditions that are fairly consistent throughout the entire year.




(a)




(b)

Figure 3: (a) Location of conducted experiments with sun path diagram, floor plans and elevation of the selected rooms with dimensions; (b) Weather conditions in Kuala Lumpur throughout a typical year with one-hour interval (ASHRAE, 2021).

Tang and Chin (2013) indicated that in Malaysia, the average peak of air temperature (dry bulb) is just below 32 °C throughout the year. The average air temperature (dry bulb) is 26.9 °C which covers day and night periods, while the minimum air temperature could be lower than 20.6 °C which mostly occurs in the early morning. On the other hand, the average global radiation is around 636 W/m$^2$ and the absolute peak global radiation could reach more than 900 W/m2 and some places could reach 1077 W/m$^2$. Furthermore, global radiation is affected by cloud cover that could reach 8 Oktas as a maximum and 6.8 Oktas as an average that can occur at any time of day. Figure 3 demonstrates the location of the office building supported by the sun path and weather conditions in Kuala Lumpur throughout a typical year. The experiments were conducted in three office rooms that have identical dimensions, areas and volumes (3.4 m length × 3m width × 3.2 m height) with the same windows dimensions and office furniture as shown in Figure 3(a). For each room, there is a glazed window that measures 2.4 m in width and 3.2 m in height and 6mm clear glass in thickness that is oriented to the south and comprises three parts (Table 3).

Table 3: Room specifications with physical properties.

| Elements | | Materials | Thickness (mm) | Conductivity W/(m·K) | Density kg/m³ | Specific Heat Capacity J/(kg·K) | Reflectance | U-Value (W/m²K) |
|---|---|---|---|---|---|---|---|---|
| 1 | Wall | Plasterboard | 12.5 | 0.2100 | 700 | 1000 | | |
| | | Cavity | 50 | - | - | - | 0.8 | 1.788 |
| | | Plasterboard | 12.5 | 0.2100 | 700 | 1000 | | |
| 2 | Floor / Ceiling | Carpet | 2 | 0.0600 | 160 | 2500 | 0.4 | 1.635 |
| | | Screed | 50 | 1.1500 | 1800 | 1000 | | |
| | | Reinforced concrete | 150 | 2.3000 | 2300 | 1000 | - | |
| | | Cavity | 50 | - | - | - | | |
| | | Plasterboard | 12.5 | 0.2100 | 700 | 1000 | 0.8 | |
| 4 | Window | Clear glass | 6 | 1.0600 | | - | | 5.597 |

The experiments were carried out in three side-by-side office spaces in passive conditions as shown in Figure 4. The test was performed during November and December, the orientation of the sun towards the south is limited within these months in the tropics where the sun angles are between 64-67 degrees (Northern Hemisphere). The study measured indoor and outdoor environmental factors that included light levels and air temperature in each room simultaneously. The study used HOBO U12/12 data loggers for indoor measurements that examined illuminance and dry bulb temperature and were utilised in previous studies (Shin et al., 2013; Hashemi, 2014; García-Solórzano et al., 2020). All data loggers and sensors were calibrated and tested before conducting the experiments. In addition, the study obtained solar irradiance, illuminance levels, dry bulb temperature and relative humidity records from a weather station nearby the tested office.

Indoor illuminance was measured on a workplane at a table height of 0.8 m above the floor in three rooms and the direction of illuminance sensors was horizontally positioned. Due to the limited depth of the tested rooms with 3m, there were two data loggers allocated in each room that were placed at 1 m and 1.5 m from the window. However, an additional light sensor connected to the microcontroller was located at 1.5 m at the centre of the room in Room A with responsive blinds. Generally, two light sensors were located in each room as followed by previous studies (Hu and Olbina, 2011; Olbina and Hu, 2012; Sun et al., 2018; Davila and Fiorito, 2021). The authors selected 1 m and 1.5 m from the window as 1 m was considered to avoid any reflections from walls and harsh light levels, 1.5 m was used to represent the centre of test rooms and the distance of 0.5 was used to understand the distribution of daylight (Do and Chan, 2020) that occurs in the first half of the room and how it affected the performance of daylighting strategies. For air temperature, the study collected the data from sensor no. 2 as shown in Figure 4 which represents the centre of the room in each case.

The interval of data collection was 1 minute in each sensor to measure the impact of fluctuation in tropical skies and test the performance and functionality of responsive blinds against these changes. However, one of the sensors in Room B with liquid glass coating was limited to 5 minute due to data storage and the period of data collection. The study observed that due to the static condition of the strategy with liquid glass coating, it was found that 5 minute intervals did not have significant differences from 1 minute.

The study applied two standards to evaluate the horizontal illuminance findings in the tested rooms. The study used Malaysian standard (MS1525:2017) and Green Building Index to assess daylight levels in an office space with workstations, the guides specify the minimum and maximum illuminance standard value for workplane between 300 lx and 500 lx, which is similar to CIBSE Guide A: Environmental Design (2015). In addition, the study used Useful Daylight Illuminance (UDI) by Nabil and Maedaljevic (2006). Furthermore, Mardaljevic et al. (2012) subdivided the range into three parts from 0 to 100 lx (non-sufficient), from 100 to 300 lx (supplementary) and from 300 to 3000 lx (autonomous), while Ko et al. (2018) used 3000 lx as an overlit where potential glare could occur > 3000 lux and classified as upper thresholds for UDI.

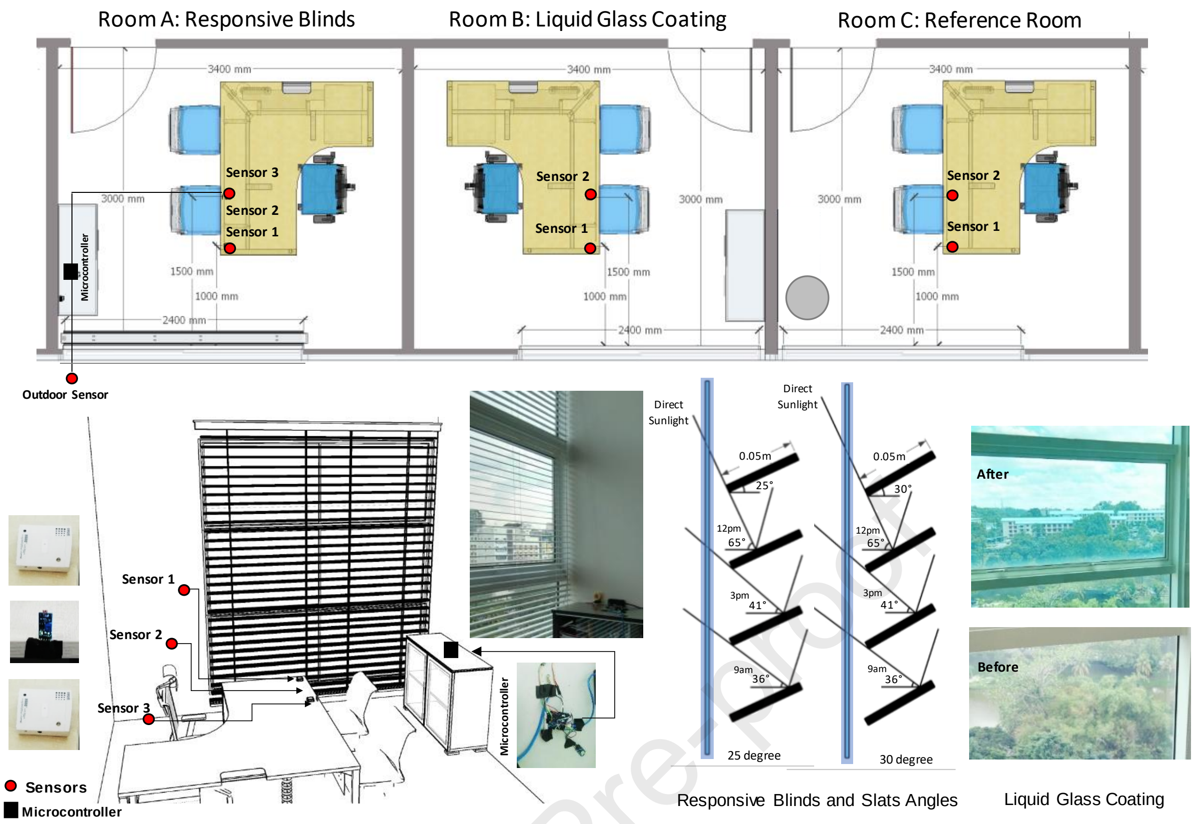



Figure 4: Schematic drawings of the field study measurement setup in three offices with measurement points.

Furthermore, the study used simulation via Radiance which is widely applied in research studies and publications and utilised in the tropics (Lim & Heng, 2016; Bahdad et al, 2021). The study tested illuminance levels and daylight glare probability in four rooms with different strategies similar to the empirical measurements and extended to assess the integration of liquid glass coating and responsive blinds. The illuminance sensors were horizontally positioned for measuring daylight levels and were vertically positioned for only examining glare levels. The study used daylight glare probability in Radiance - IESVE software to assess glare from a hemispherical fish-eye using a luminance image (Chaloeytoy et al., 2020; Liu et al., 2021). The study used a position of the eye (view) of 1.35 m (seated man) to measure DGP. The DGP provides a percentage of people who would be satisfied in the form of Imperceptible (less than 35 %), Perceptible (35 % - 40 %), Disturbing (40 % - 45 %) and Intolerable (greater than 45 %). DGP was used by several studies to assess discomfort glare levels when there is no direct sunlight in the field of view (Wienold and Christoffersen, 2006; Wienold, 2007), if not, errors up to 20 % were estimated (Kleindienst and Andersen, 2009).

The study targeted three critical times 9am, 12pm and 3pm, these times are utilised by previous studies (Lim et al., 2012; Lim & Heng, 2016). The orientation of the sun-facing south facade is limited to three months between October and December or December and February which represent the highest and the lowest sun angles. The study targeted November to demonstrate average daylight glare probability.

On the other hand, the technical guideline for passive design in Malaysia by Tang and Chin (2013) indicated that 25.75 °C considers thermally acceptable while 28.25 °C represents the acceptable upper limit of indoor temperature that provides a tolerable thermal environment. As this research only explored environmental performance, the study only refers to these values in the analysis to identify the impact of maximum indoor air temperatures in each room.

Figure 5 demonstrates the research steps and assessment process. The study is developed based on a systematic investigation to assess the performance of each strategy and technology. As a result, the study consists of three stages that were conducted to measure and evaluate the performance of daylight and thermal conditions. Due to the large amount of data that was collected every minute, the study presents three days, as utilised in previous studies performed in a hot and humid climate (Ismail, 2010; Ong, 2011; Al-Obaidi et al., 2017). These days were targeted to demonstrate 3 continuous days with almost dry conditions to examine the impact of solar access and accumulative heat in indoor spaces. Due to fluctuations in outdoor conditions, the study found 3 continuous days at the end of November as 21, 22 and 23 to reveal these characteristics. In addition, by analysing the sun path and sun position on the south façade, the sun angle on selected days was around 65 degrees at midday near the minimum of 64 degrees in December. The selected days demonstrated dry conditions with an intermediate sun that presented typical conditions that occur around the year in Malaysia as shown in Figure 3. On the other hand, the simulation analysis helped the study to examine the impact of DGP at different times. Solstice and equinox dates as 21 Dec, 21 March, 21 June, 21 September and 21 November as one of the selected days were chosen to demonstrate the impact.

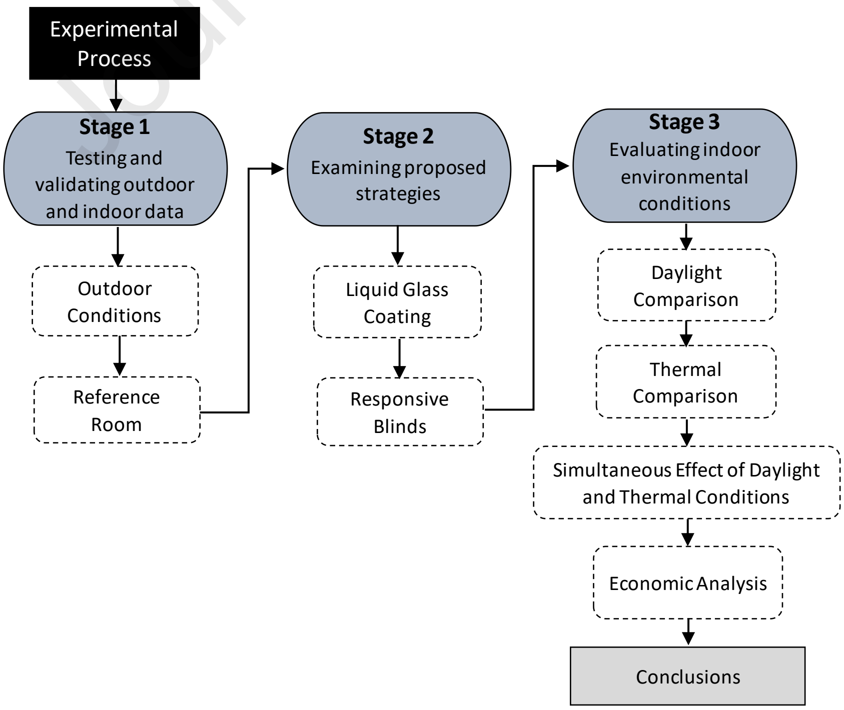



Figure 5: Research steps and assessment process.

## 3. Results and Discussion

### 3.1 Testing and validating outdoor and indoor environmental conditions

This section is important in this research to (i) demonstrate the reliability of data collection for empirical and simulation analyses, (ii) examine environmental conditions that control the performance of indoor spaces to provide robust findings and (iii) set clear research boundaries. In this stage, the study presented the essential findings by demonstrating minimum and maximum outdoor and indoor conditions in a conventional office building in the tropics. The analyses were provided to assess the study quality by examining the selected days and testing the case study which demonstrates the reference room to develop this experimental research. This section is divided into evaluating outdoor environmental conditions and testing the indoor environmental conditions of the reference room.

#### *3.1.1 Outdoor weather conditions of the selected days*

The study conducted a series of tests to assess the data collection for three days that were used in this study. Figure 6 presents the outdoor weather conditions that cover solar irradiance, illuminance, air temperature and relative humidity during the selected days. The readings in Figure 6(a) indicated that solar irradiance and illuminance levels were almost steady but they experienced fluctuations and peaked around the middle of the day. The average readings were between 298 W/m$^2$ and 339 W/m$^2$ for solar irradiance and 33500 lx and 37900 lx for outdoor illuminance. While the maximum readings from solar irradiance and illuminance levels for three days ranged between 613 W/m$^2$ and 680 W/m$^2$ and 65622 lx to 72300 lx, respectively. Figure 6(b) demonstrates outdoor air temperatures and relative humidity, the maximum was 32.1 °C and 90 %, respectively. On average, it was 28.1 °C and 73 %, while the minimum was 25 °C and 52 %, respectively. The findings in these selected days clearly reflected the conditions of typical days in Kuala Lumpur as shown in Figure 3(b) and discussed in the materials and methods section.

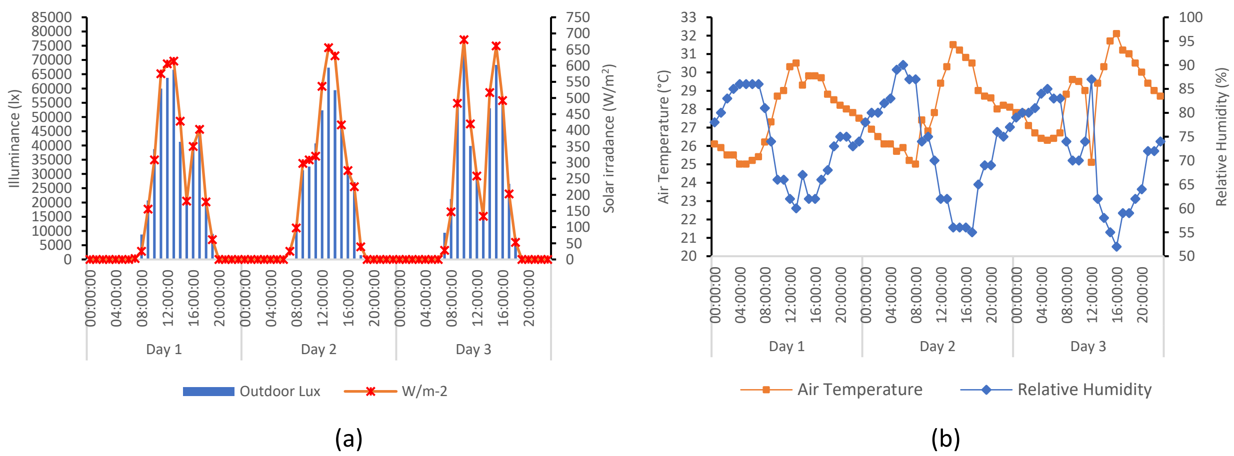



Figure 6: Hourly outdoor weather data during the investigation: (a) Outdoor illuminance and solar irradiance; (b) Outdoor air temperature and relative humidity

### *3.1.2 Indoor environmental conditions of the reference room*

Figure 7(a) presents the readings of illuminance from two sensors at 1 minute intervals. Both sensors recorded high illuminance levels that were beyond useful daylight illuminance (UDI). The readings indicated that both sensors were very sensitive at 1 minute intervals that demonstrated significant fluctuations in their readings. The data showed that illuminance in sensors 1 and 2 reached the maximum level around 17345 lx and 14925 lx, while the average level was 4729 lx and 3353 lx, respectively.

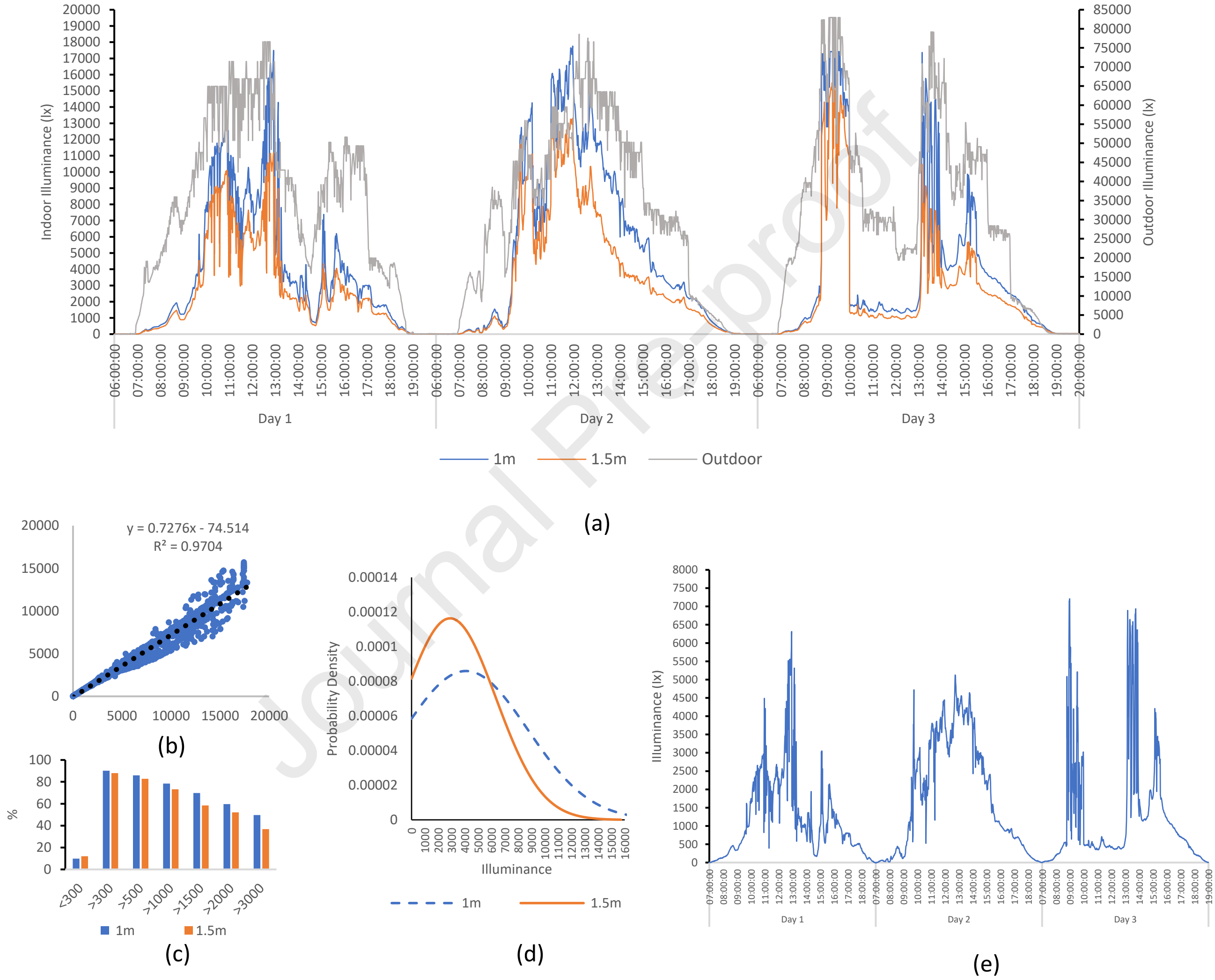



Figure 7: (a) Illuminance levels from two sensors in the reference room; (b) Correlation analysis of illuminance levels between sensors 1 & 2; (c) Percentage chart of illuminance levels with UDI classifications for sensors 1 & 2; (d) Normal probability distribution plot for sensors 1 & 2; (e) Differences in daylight levels between sensors 1 & 2 in the reference room.

Figure 7(c) shows that 87.9 - 90.15 % of illuminance levels were above 300 lx, while 82.85 – 86 % were above 500 lx. In fact, illuminance readings showed that in the range >3000 lx, sensor 1 with 1 m showed 49.7 %, while sensor 2 with 1.5 m exhibited 36.85 %. To support the correlation analysis in Figure 7(b), which shows a high correlated value but scattered at high illuminance levels, Figure 7 (d) demonstrates the analysis of normal probability distribution in sensors 1 and 2. The findings in sensor 1 indicated that the median is 2140 lx and the higher probability in the form of the mean is 4078 lx. While for sensor 2, the median is 1509 lx and the mean is 2893 lx. The probability distribution clearly demonstrated variance that spread between the sensors. The findings showed that the area under the normal distribution curve between 300 lx and 2000 lx for sensor 1 is about 24 %, while for sensor 2 is about 32 %. Figure 7(e) reveals the differences between sensors 1 and 2 that presented the impact of daylight distribution in the room. The findings indicated that for three days, the maximum difference ranged between 5092 lx and 7135 lx, while the average difference occurred between 1270 lx and 1890 lx.

Figure 8 demonstrates the thermal conditions of the reference room during the selected days. It was noticed that outdoor air temperatures were directly impacted by solar irradiance. The readings of indoor air temperatures showed that the maximum values varied between 28.86 °C and 30.50 °C, which occurred after 1 pm, while the minimum values ranged between 24.36 °C and 24.86 °C that was mainly during the early morning. The average readings fluctuated between 26.40 °C and 27.27 °C. As this study was conducted for several days to understand the impact of outdoor conditions on the indoor environment, Figure 8(b) provided the findings that resulted from the analysis based on assessing the differences between outdoor and indoor air temperatures (Difference = outside – inside) to set the boundary for each investigated strategy. The analysis showed that the maximum differences were between 2.41 °C and 4.68 °C, which occurred between 8am and 4pm, while the minimum differences were higher than the outdoor and generated negative values of -1.36 °C and -0.80 °C, which occurred after midnight until 7am.

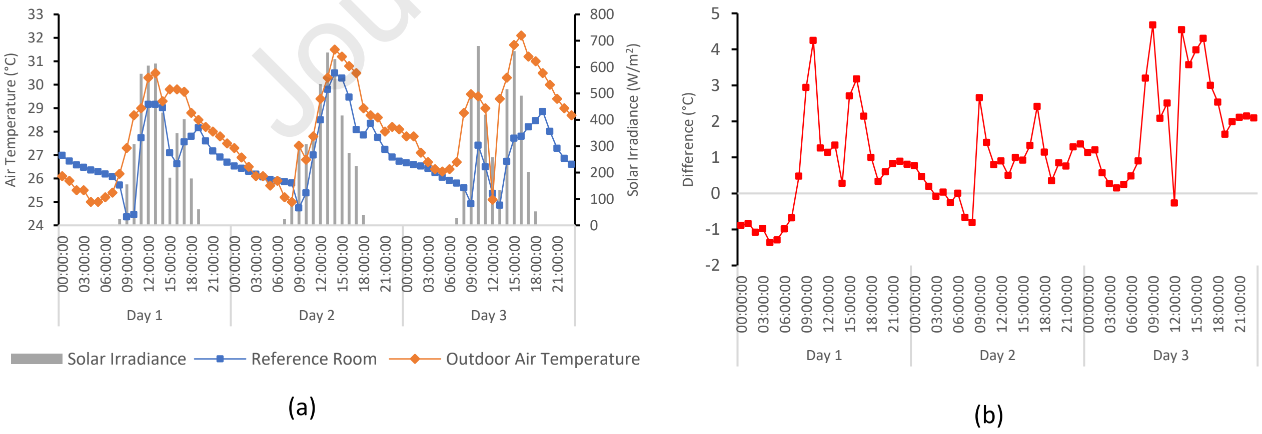



Figure 8: (a) Indoor and outdoor air temperatures in the reference room; (b) Differences between outdoor and indoor air temperatures.

### 3.2 Examining the performance of proposed daylighting strategies

In this stage, the study investigated the performance of two rooms with different daylighting strategies to assess their impact on the indoor environment. This section is divided into two parts that cover liquid glass coating and responsive blinds with a similar analysis structure to the reference room to maintain research clarity and systematically investigated the research study.

### *3.2.1 Indoor environmental conditions of the room with liquid glass coating*

Figure 9(a) demonstrates the performance of indoor illuminance within two sensors. The recorded data showed that illuminance levels in sensors 1 and 2 reached the maximum of around 5061 lx and 4289 lx, while the average varied between 1567 lx and 1324 lx, respectively. Both maximum and average outcomes are above standards, however, the average outcomes are within the UDI. The study conducted a correlation analysis to assess the impact of daylight distribution simultaneously from sensors at different points in the room. The analysis revealed a strong correlation of 0.97 and it was noticed that liquid glass coating managed to reduce the differences in daylight levels between both sensors which improved daylight distribution compared to the reference room.

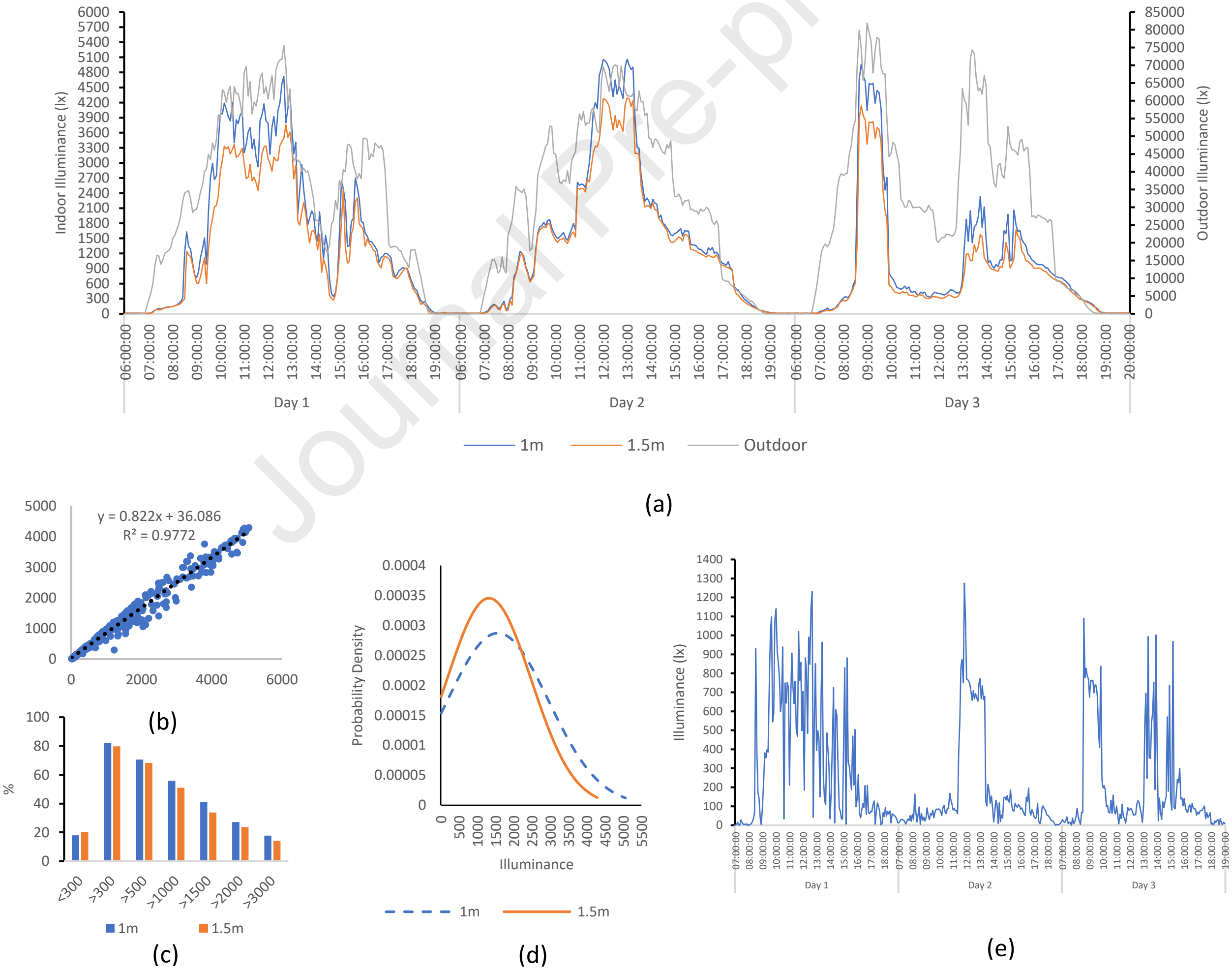
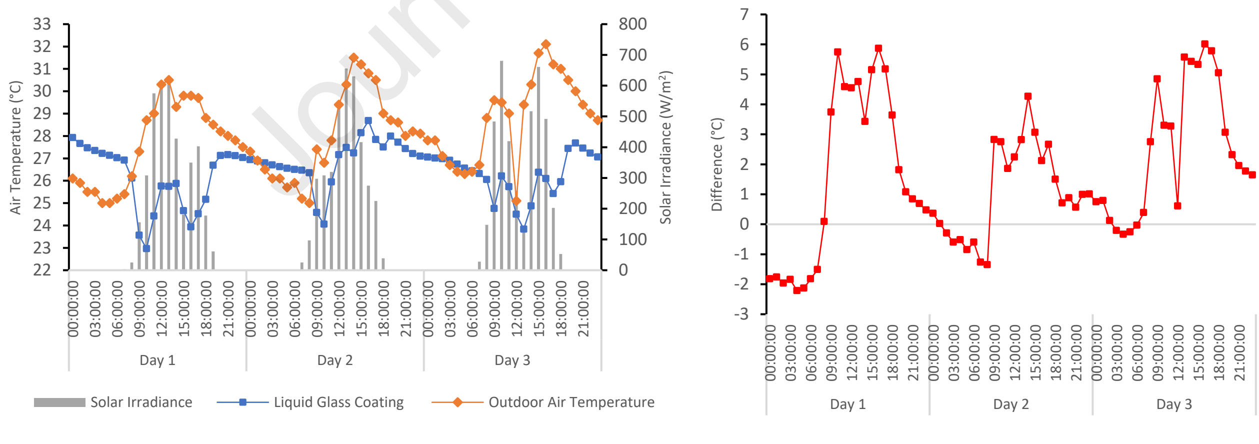



Figure 9: (a) Illuminance levels from two sensors in the room with liquid glass coating; (b) Correlation analysis of illuminance levels between sensors 1 & 2; (c) Percentage chart of illuminance levels with UDI classifications for sensors 1 & 2; (d) Normal probability distribution plot for sensors 1 & 2; (e) Differences in daylight levels between sensors 1 & 2 in the room with liquid glass coating.

Furthermore, the study classified the percentage of illuminance levels in both sensors as shown in Figure 9(c) and found that around 79.77 – 82 % was above 300 lx, while 68.28 - 70.5 % was above 500 lx. The analysis of illuminance readings showed that in the range >3000 lx, sensor 1 with 1m demonstrated 17.7 %, while sensor 2 with 1.5m showed 14 %. Figure 9 (d) demonstrates the analysis of normal probability distribution in sensors 1 and 2. The findings in sensor 1 revealed that the median is 1200 lx and the higher probability in the form of the mean is 1378 lx. While for sensor 2, the median is 1045 lx and the mean is 1215 lx. The probability distribution showed some variances between the sensors. The findings indicated that the area under the normal distribution curve between 300 lx and 2000 lx for sensor 1 is about 52 %, while for sensor 2 is about 58 %. In addition, Figure 9(e) shows the differences between sensors 1 and 2 that exhibited the impact of daylight distribution in the room. The results revealed that for three days, the maximum difference ranged between 1090 lx and 1274 lx, while the average altered between 190 lx and 343 lx.

Figure 10(a) displays the thermal conditions of the tested room during the selected days. The recorded data of indoor air temperatures demonstrated that the maximum readings fluctuated between 27.6 °C and 28.68 °C, which occurred after 4pm and 6pm, while the minimum readings ranged between 22.96 °C and 24.05 °C, which mostly occurred during the morning. The average results were between 26.10 °C and 26.91 °C. Figure 10(b) demonstrates the differences between outdoor and indoor air temperatures. It was observed that the maximum varied between 4.26 °C and 6 °C that occurred between 8am and 6pm, while the minimum fluctuated between -2.22 °C and -0.34 °C, which happened after midnight until 7am.




(a) (b)

Figure 10: (a) Indoor and outdoor air temperatures in the room with liquid glass coating; (b) Differences between outdoor and indoor air temperatures.

### *3.2.2 Indoor environmental conditions of the room with responsive blinds*

In this section, the study investigated indoor environmental conditions in the room with responsive blinds during the selected days. Figure 11(a) demonstrates the behaviour of indoor illuminance in two sensors. Figure 11(b) presents a correlation analysis to assess the impact of daylight distribution simultaneously at different points in the room, the findings showed a strong correlation of 0.99

between the two sensors. The analysis demonstrated a high degree of fitting in daylight readings that revealed the functionality of responsive blinds to block direct solar access in terms of sunlight, which improved daylight distribution. Both sensors recorded illuminance levels within an acceptable range by the standards. However, the study found that the system was limited by its operation to respond in seconds to light levels as the device was dynamic and moveable to adjust the slats to meet the range of 300-500 lx. The recorded data showed that the illuminance level in sensors 1 and 2 reached the maximum of about 646 lx and 588 lx, while the average ranged between 412 lx and 375 lx, respectively.

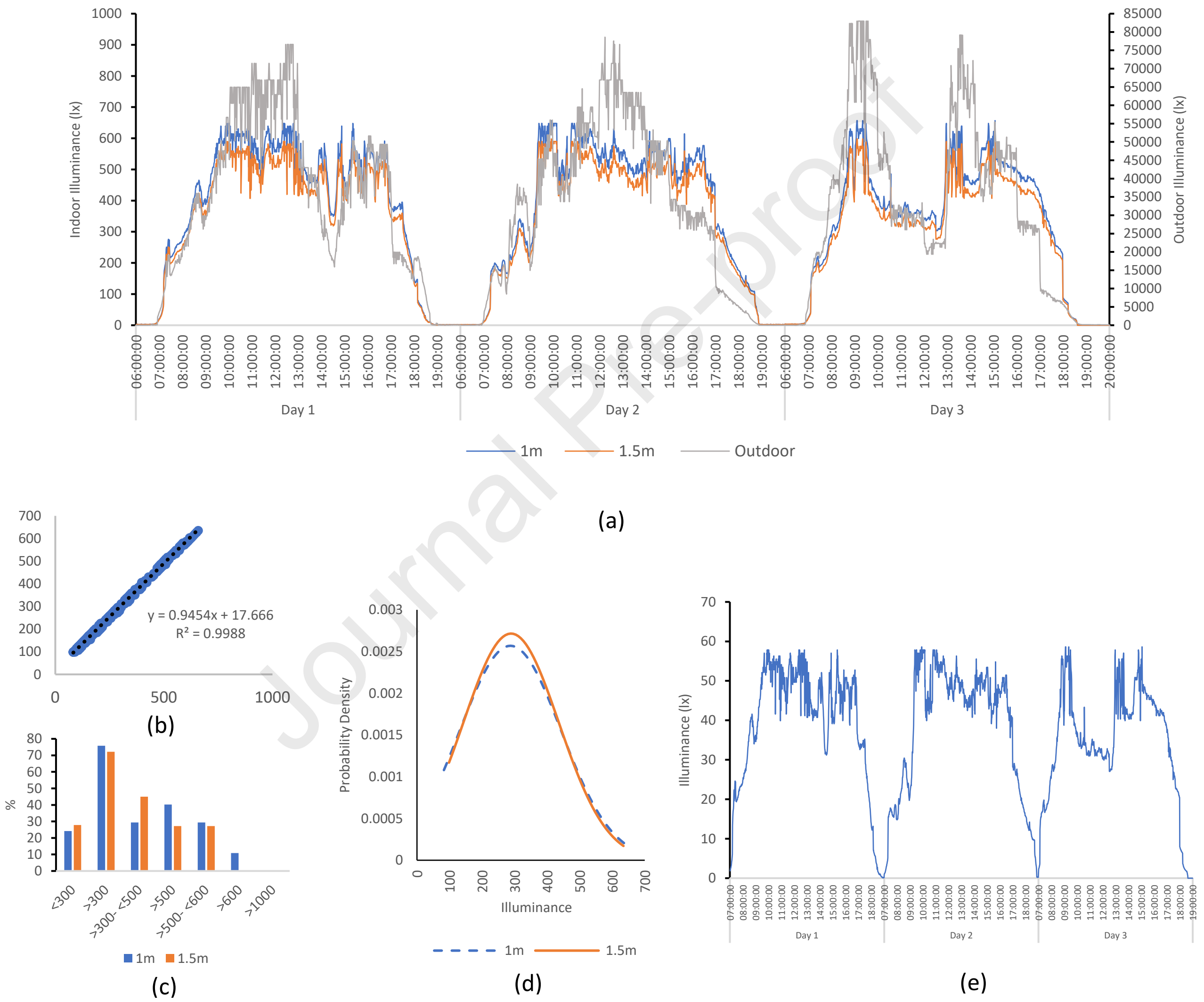
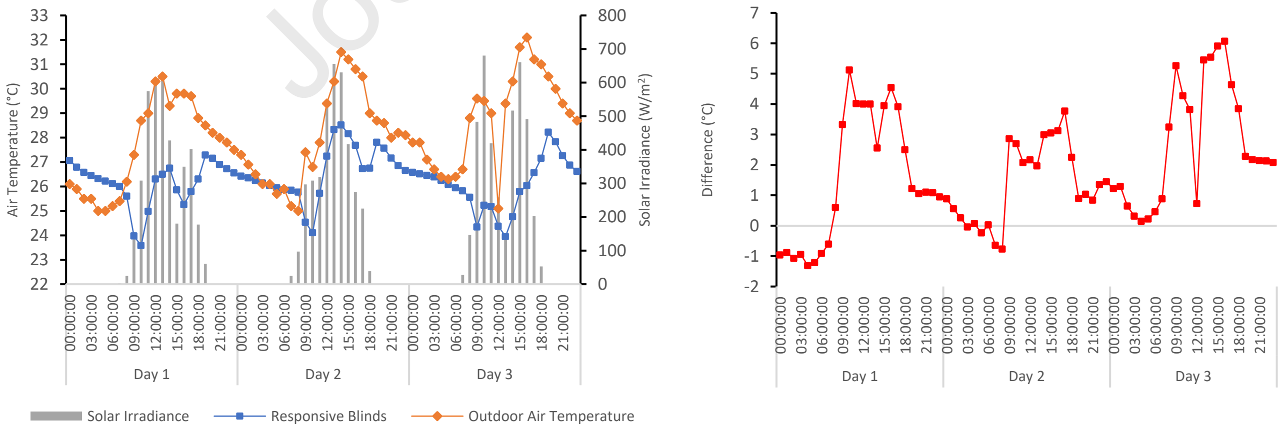



Figure 11: (a) Illuminance levels from two sensors in the room with responsive blinds; (b) Correlation analysis of illuminance levels between sensors 1 & 2 ;(c) Percentage chart of illuminance levels with UDI classifications for sensors 1 & 2; (d) Normal probability distribution plot for sensors 1 & 2; (e) Differences in daylight levels between sensors 1 & 2 in the room with responsive blinds.

The study analysed and classified the percentage of illuminance levels in both sensors as shown in Figure 11(c), it was found that around 72.17 - 75.82 % was above 300 lx, while 27.23 - 40.22 % was above 500 lx. However, it was observed that sensor 2 which was connected to the microcontroller did not record data above 600 lx. The analysis showed that sensor 2 was capable to maintain 72.77 % of recorded data below 500 lx. However, sensor 1 recorded 10.82% above 600 lx but there were no data above 646 lx. Figure 11 (d) demonstrates the analysis of normal probability distribution in sensors 1 and 2. The findings in sensor 1 revealed that the median is 264 lx and the higher probability in the form of the mean is 317 lx. While for sensor 2, the median is 268 lx and the mean is 319 lx. The probability distribution between the sensors demonstrated low variance. The findings showed that the area under the normal distribution curve between 300 lx and 600 lx for sensor 1 is about 66 %, while for sensor 2 is about 71 %. In addition, Figure 11(e) shows the differences between sensors 1 and 2 that exhibited the impact of daylight distribution in the room during the three studies. It was noticed that the maximum varied between 56.2 lx and 58.62 lx, while the average fluctuated between 29.2 lx and 43.76 lx. The outcomes from this analysis indicated a high level of uniformity in daylight distribution.

Figure 12(a) demonstrates the thermal conditions of the room with responsive blinds during the selected days. The data of air temperatures revealed that the maximum values ranged between 27.28 °C and 28.51 °C, which mostly occurred after 4pm, while the minimum values varied between 23.58 °C and 24.10 °C, which mostly appeared during the morning. However, the average fluctuated between 26.07 °C and 26.60 °C. Figure 12(b) shows the differences between outdoor and indoor air temperatures. The analysis revealed that the maximum difference ranged between 3.77 °C and 6.06 °C, which mostly occurred between 8am and 6pm. However, the minimum difference was observed to be higher than the outdoor and generated negative values of -1.31 °C and -0.77 °C which mostly occurred after midnight until 7am.




(a) (b)

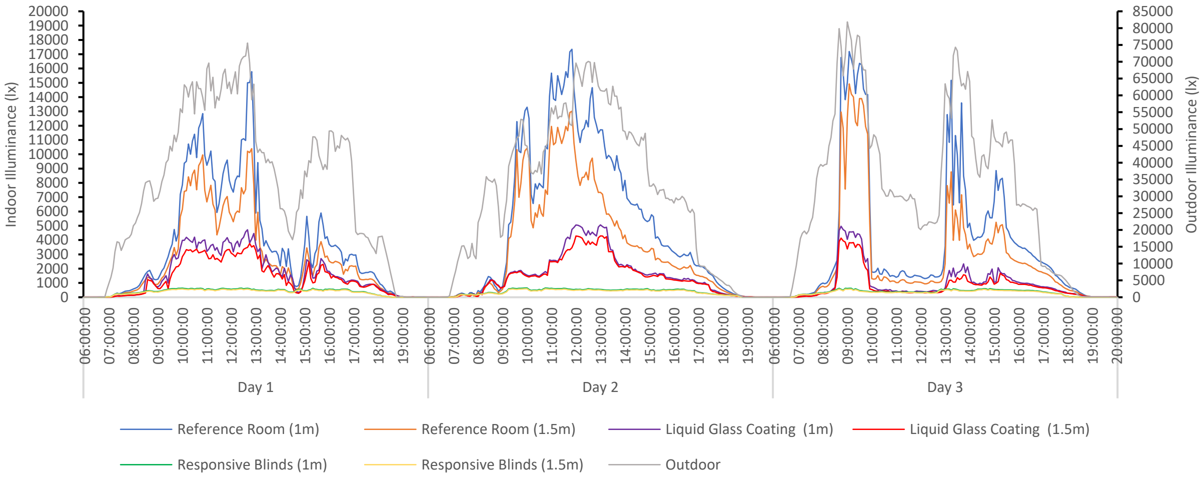
Figure 12: (a) Indoor and outdoor air temperatures in the room with responsive blinds; (b) Differences between outdoor and indoor air temperatures.

### 3.3 Evaluating indoor environmental conditions of rooms with different daylighting strategies

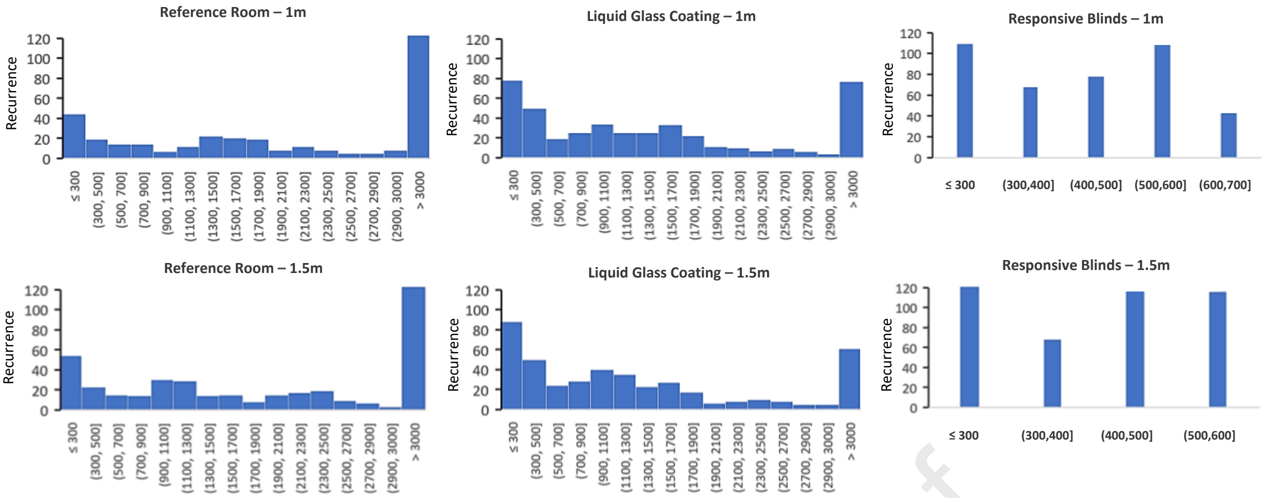
This stage presents the indoor environmental performance of tested daylighting strategies and examines their performance against the reference room. In empirical measurements, three rooms were tested to evaluate indoor environmental conditions in the form of daylight and thermal conditions. However, in the simulation, four rooms were assessed to examine daylight conditions using Radiance in all strategies as well as the integration of liquid glass coating with responsive blinds. Due to the large number of collected data, this section presents the results of field measurements at 5 minute intervals. The analysis also investigated the simultaneous effect of daylight and thermal conditions in the field study during the measurement days. In addition, an economic analysis using the life cycle cost assessment was performed to demonstrate the viability of the proposed strategies.

#### *3.3.1 Daylight Conditions*

Figure 13 shows the performance of daylight in three different rooms with three different daylighting strategies. Figure 13(a) indicates that maximum readings for the reference room in sensors 1 and 2 were around 17345 lx and 14925 lx, liquid glass coating were around 5061 lx and 4289 lx, while responsive blinds were around 646 lx and 588 lx, respectively. The analysis showed that the reference room experienced high fluctuations between 10am and 4pm due to outdoor illuminance levels that significantly impacted indoor daylight performance. The fluctuations in the liquid glass coating showed more stability and were less impactful compared to the reference room. The fluctuations were within a thousand lx and sometimes less during the peak hours. Also, it was found that maximum readings were above UDI, however, they were not significantly higher compared to the reference room. The room with liquid glass coating managed to reduce the maximum readings between 10000 lx and 12000 lx due to the properties of the material at the nanoscale to diffuse light. Finally, it was noticed that the room with responsive blinds performed the best and managed to cut the fluctuations by providing almost constant readings from 9am until 5pm.




(a)




(b)

Figure 13: (a) Illuminance levels from sensors 1&2 in three rooms; (b) Recurrence of illuminance levels in 1m and 1.5m from the window.

Figure 13(b) demonstrates a recurrence quantification analysis of collected data to understand the behaviour of light levels (Mettanant and Chaiwiwatworakul, 2014; Fathoni et al., 2016; Ko et al. 2018) between < 300 lx and > 3000 lx in each point. The analysis of daylight levels in liquid glass coating showed a stability in recurrence readings between <300 and >3000. The analysis revealed that in both sensors, readings between 300 lx and 500 lx were the highest followed by levels that represent a close distribution in the range between 500 lx and 1900 lx. These findings showed that liquid glass coating demonstrated an acceptable performance to distribute light within this range. However, this strategy could not overcome the light levels that recurred above 3000 lx. On the other hand, the room with responsive blinds exhibited a strong control that limited the levels to be over UDI. It was observed that in sensor 1, the maximum recurrence ranged between 500-600 lx and below 300 lx, while sensor 2 performed in a similar way and demonstrated further stability except for readings between 300-400 lx.

Further analysis was required to assess the comfort level with these strategies that was not possible to identify by horizontal illuminance and field measurements, therefore, the study utilised Radiance simulation to assess the impact of glare in the rooms. Figure 14(a) demonstrates the correlation analysis of illuminance levels between field measurements and Radiance in IESVE software. The finding indicated a strong correlation of 0.97 that was helpful to develop the models based on information provided in section 2 and data presented in Stage 1 and Stage 2 within this section. The analysis helped to test all strategies and develop a new approach that integrates liquid glass coating with responsive blinds in Room 4.

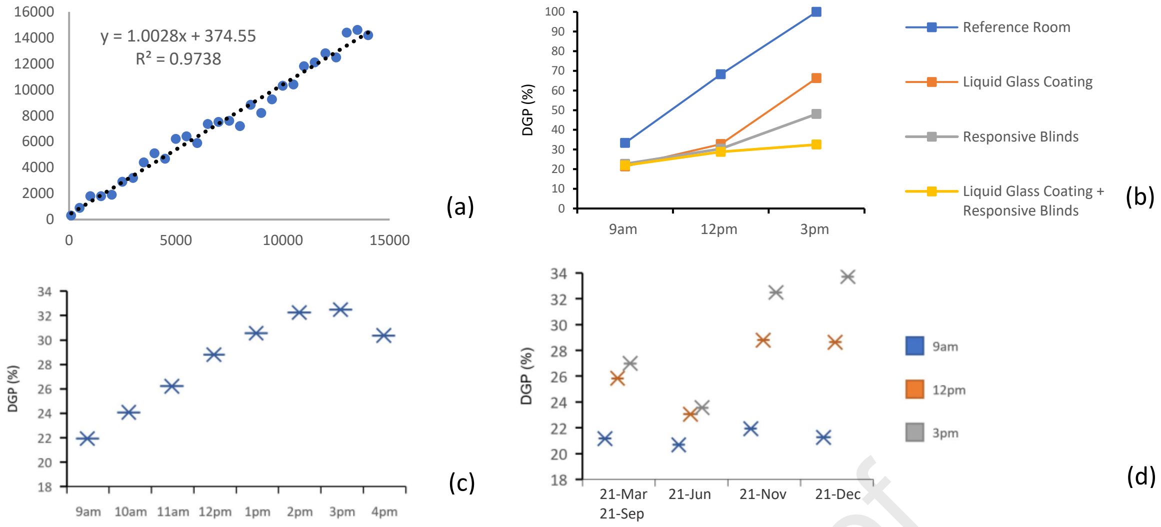



Figure 14: (a) Correlation analysis of illuminance levels between Radiance and empirical data; (b) DGP for different strategies via Radiance; (c) DGP for responsive blinds; (d) DGP for the integrated strategy.

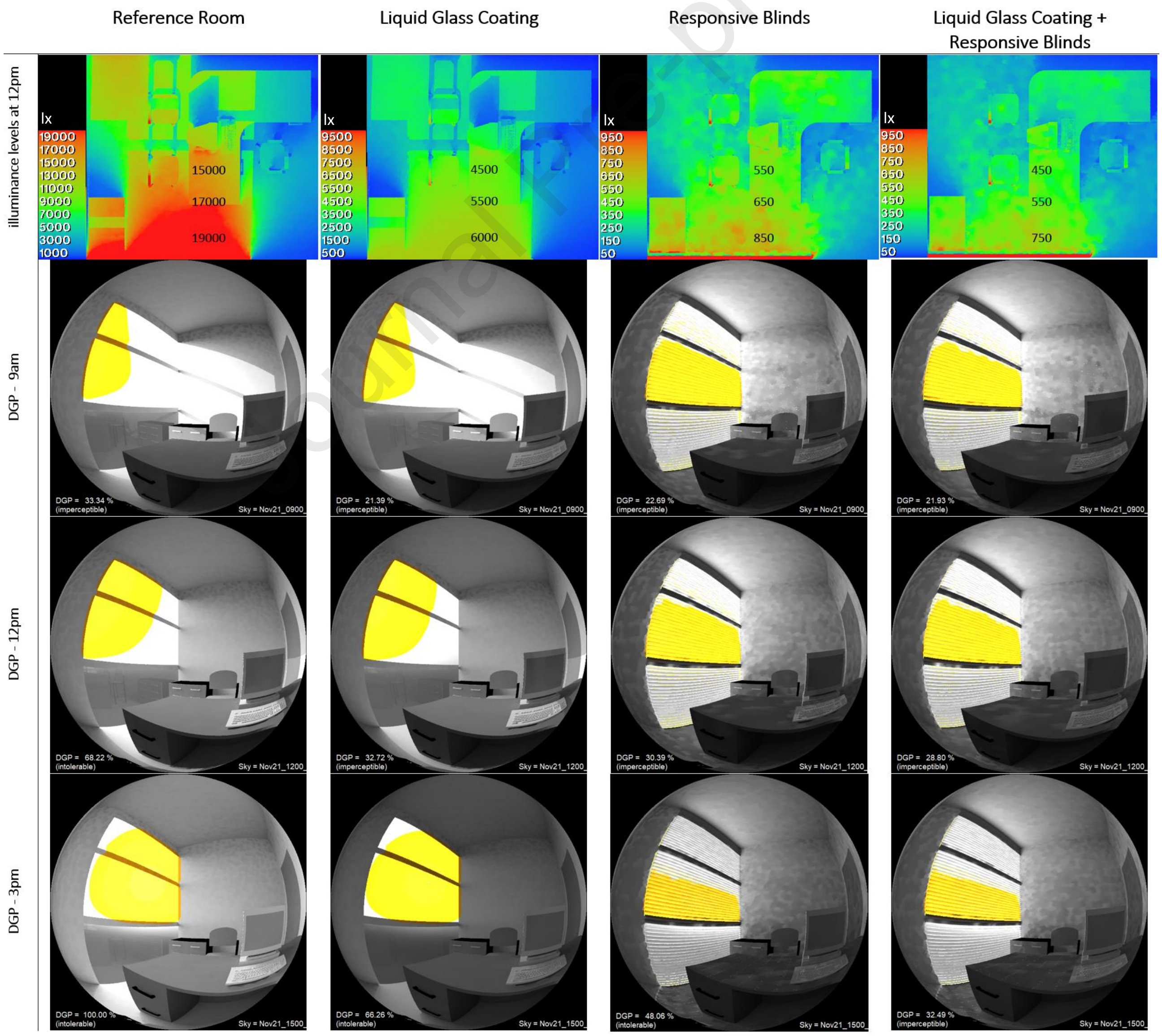



Figure 15: Illuminance analysis and daylight glare probability to assess different daylight strategies in Radiance.

Figure 14(b) demonstrates the findings of DGP analysis that is presented in Figure 15 using illuminance analysis and viewing via hemispherical fish-eye Radiance. The selected hours (9am, 12pm and 3pm) demonstrate the critical times of low and high sun angles from different orientations on the south facade that were utilised in previous studies in the tropics (Lim et al., 2012; Lim and Heng, 2016). The targeted day in Figure 14(b) was 21 November as one of the selected days in the field measurements. The findings in Figure 14 (b) indicated the possibility for responsive blinds to achieve lower DGP compared to others, therefore, the study critically examined the performance of DGP between 9am and 4pm on the same day as 21 November to examine the validity of selected hours in Figure 14(c). The findings in Figure 14(c) showed that 3pm recorded the maximum DGP that helped to confirm the chosen hours and performed a further analysis in Figure 14(d) that examined the performance of the integrated strategy in different solstice and equinox periods.

All rooms in Figure 15 have identical dimensions and orientation, Room 4 on the right was developed in the simulation to integrate daylight strategies from rooms 2 and 3 (Liquid Glass Coating + Responsive Blinds). According to the orientation of the office desk and computer position, liquid glass coating and responsive blinds managed to provide imperceptible values of 21.39 % and 22.69 %, respectively at 9am and imperceptible values of 32.72 % and 30.39 %, respectively at 12pm. However, both strategies failed to provide comfortable levels at 3pm. The findings indicated intolerable values of 66.26 % and 48.06 %, respectively at 3pm. Therefore, the study extended the capability of liquid glass coating to diffuse light and responsive blinds to control solar access and light in one system that was developed in Radiance to assess the glare issue. The new integration indicated that the system is capable to control daylight and lower the values of Daylight Glare Probability at three times 9am, 12pm and 3pm by providing imperceptible values of 21.93 %, 28.8 % and 32.49 %, respectively, as shown in Figure 15. Figure 14(d) shows DGP analysis using the integrated strategies in different solstice and equinox periods. The findings indicated that with the lowest sun angle in Malaysia on 21 Dec with 36° at 9am, 41° at 3pm and 65° at 12pm, DGP analysis showed a maximum value of 33.71 % (Imperceptible).

***3.3.2 Thermal Conditions***

Figure 16(a) shows the comparison of indoor air temperatures in three rooms with different daylighting strategies. The recorded data demonstrated that indoor air temperatures were different in each strategy. In the reference room, the data showed that the maximum value was 30.50 °C, the average was 26.97 °C and the minimum was 24.36 °C. In the room with liquid glass coating, the maximum value was 28.68 °C, the average was 26.43 °C and the minimum was 22.96 °C. Finally, in the room with responsive blinds, the maximum value was 28.51 °C, the average was 26.27 °C and the minimum was 23.58 °C. The findings of maximum air temperatures in the reference room were higher than 28.25 °C which represents the acceptable upper limit in the tropics, however, they were close in the rooms with liquid glass coating and responsive blinds. Furthermore, Figure 16(b) shows the analysis of the recurrence rate of indoor air temperatures in each room. The findings indicated that in both rooms the reference and the responsive blinds recorded the maximum rate of 26 °C, however, the room with liquid glass coating demonstrated the maximum rate at 27 °C. On the other hand, the results showed that the room with liquid glass coating was capable to keep air temperatures below 23 °C and a maximum of 27 °C, while the reference room only achieved 24 °C as a minimum and 30 °C as a maximum.

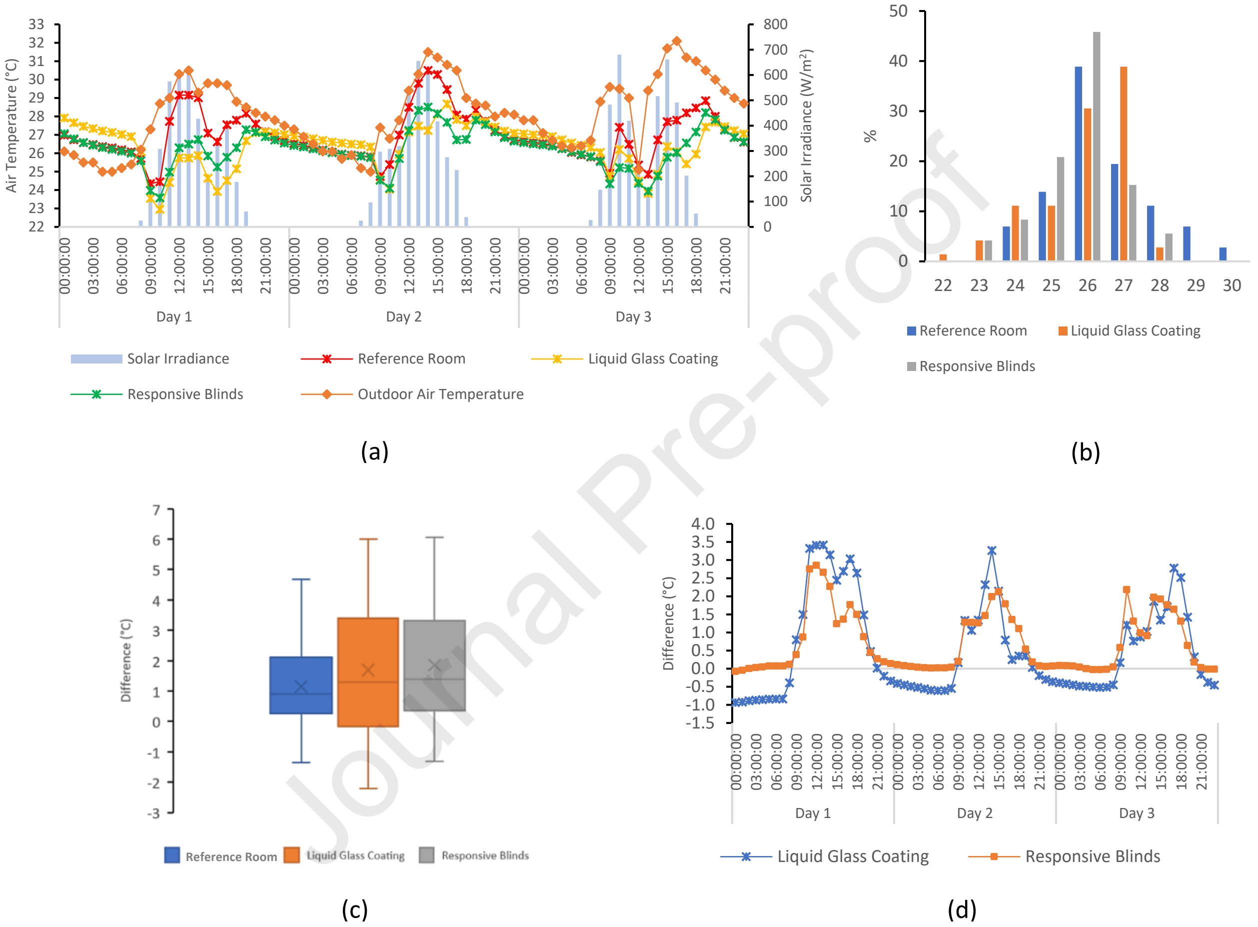



Figure 16: (a) Indoor and outdoor air temperatures in three rooms; (b) Recurrence rate of indoor air temperature in three rooms; (c) Difference between outdoor and indoor air temperatures; (d) Difference between reference room and tested rooms.

From the analysis above, it could be observed that the room with liquid glass coating did not clearly demonstrate the difference against the room with responsive blinds. Therefore, Figure 16(c) shows the performance of thermal conditions in all rooms. Figure 16(c) demonstrates the differences in air temperatures between (outdoor – indoor) that are presented using a boxplot diagram. This analysis was conducted to understand the performance of indoor conditions that was used by several studies in the tropics (Qahtan et al., 2011: Al-Obaidi et al., 2014). The analysis showed that the reference room has the lowest difference compared to other strategies, the maximum difference achieved in this room was around 2 °C between the first and third quartile. However, the room with liquid glass coating showed the best performance in the differences between the first and third quartile which was 3.5 °C. Compared to the room with responsive blinds, it was observed that the difference between the first and third quartile was 3.3 °C, however, it was noticed that the median was higher than all rooms with 1.85 °C. Furthermore, to clarify the differences between the rooms with proposed daylighting strategies, further analysis was conducted to examine the strategies against the reference room. Figure 16(d) demonstrates the analysis of differences between (reference room – liquid glass coating) and (reference room – responsive blinds). The results indicated that the room with liquid glass coating managed to achieve a maximum reduction between 2.78 °C and 3.42 °C, while the room with responsive blinds achieved a reduction between 2.12 °C and 2.86 °C. However, for the minimum readings, the responsive blinds recorded higher air temperature than the reference room by -0.08 and -0.03, while the room with liquid glass coating kept indoor heat to be built up and had higher air temperature compared to the reference room that exceeded by -0.93 and -0.45.

As this study was conducted in a passive condition with no ventilation, it was noticed in the room with liquid glass coating the capability of Sol-Gel technology at nano levels to block more than 90 % of near-infrared radiation and maintain more than 70 % of visible light which helped to reduce solar gain and lower temperature effectively. However, it was observed that the heat had built up in the room during the night which was higher than other strategies. In addition, the heat slowly dissipated due to the impact of the low U-Value for this coating and the characteristics of thermal mass in the structural elements of the room. On the other hand, responsive blinds provided an insulating capability that reduced heat gains through their reflective white slats which reflected most of the heat that fell on them. The collected data showed that clear glass in the reference room and responsive blinds demonstrated a similar pattern at night until early morning which indicated the impact of thermal conductivity of clear glass to lose the absorbed heat quickly.

### *3.3.3 Simultaneous effect of daylight and thermal conditions*

Ko et al. (2018) performed a simultaneous analysis of luminous and thermal autonomy by integrating hourly data visualizations using a colour scheme. According to Ko et al. (2018), these visualizations allow designers and engineers to understand the behaviour of thermal and illumination conditions when they occur throughout a specific period. As a result, the study demonstrated this approach by exploring the impact of daylight and thermal conditions in the tested rooms to understand their performance using 5 minute intervals.

Figure 17 presents the analysis of illuminance, air temperature and time during the measurement days to understand the simultaneous effect. In addition, the analysis is supported by percentages based on a developed scale for the tropics to visualise the simultaneous effect. The analysis exhibited the coverage of different indoor illuminance levels compared to indoor air temperatures between 7am and 7pm. By analysing the results in Figure 17, the heat map charts clearly demonstrated that the strategy of responsive blinds as shown in Figure 17(c) provided the most controlled and evenly distributed illuminance levels between 300 lx and 600 lx within different air temperatures that ranged between 23.6 °C and above 28.6 °C. The analysis showed that 41 % of collected data was between 300-600 lx and thermally acceptable while 25% of data was between 300-600 lx and thermally acceptable (upper limit) that occurred between 8am and 5pm. However, only 5 % was between 300-600 lx and thermally unacceptable which only occurred on Day 2 between 1pm and 3pm. On the other hand, it was noticed that early morning and evening periods were underlit. The analysis of these periods showed that 21 % of data was >300 lx and thermally acceptable (upper limit). The reason for high air temperatures during early morning and evening periods is justified to be related to heat build-up due to the characteristics of passive conditions in an enclosed space.



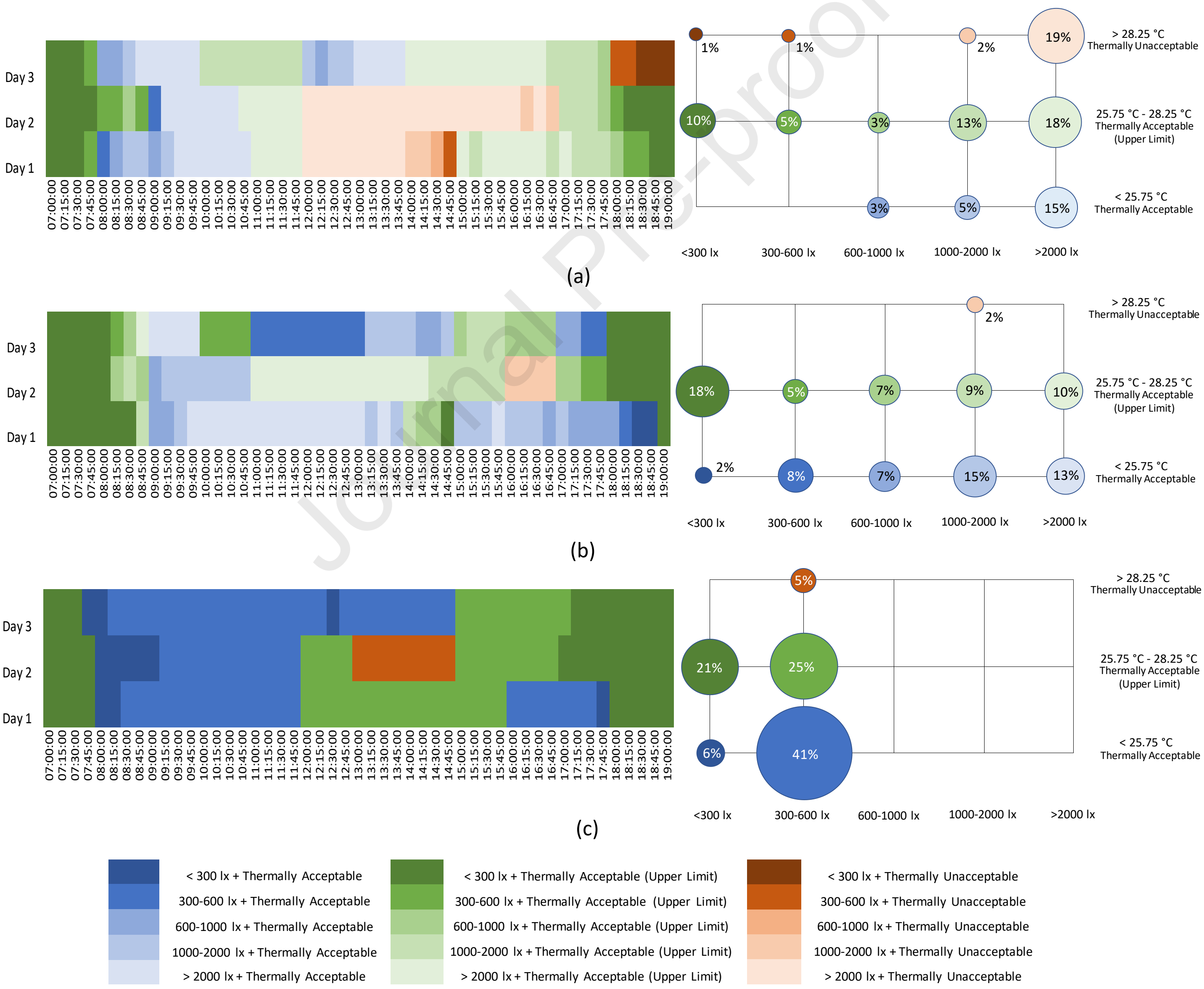



Figure 17: Simultaneous analysis of illuminance, air temperature and time during the measurement days to demonstrate indoor performance at the centre of each room: (a) Reference, (b) Liquid Glass Coating and (c) Responsive Blinds.

On the other hand, Figure 17(b) demonstrated the results from the room with liquid glass coating, the findings showed that this strategy demonstrated different ranges of illuminance levels that were thermally acceptable between lower and upper limits. However, it demonstrated a lower percentage for thermally unacceptable which was 2 % compared to the room with responsive blinds which was 5%. This percentage only occurred when illuminance levels were between 1000 lx and 2000 lx. The analysis showed that only 8 % was between 300-600 lx and thermally acceptable, while 5 % was between 300-600 lx and thermally acceptable (upper limit). The analysis showed that 28 % was above 1000 lx and thermally acceptable, while 19 % was above 1000 lx and thermally acceptable (upper limit).

Comparing both strategies against the reference room showed that the reference room experienced high illuminance levels that were mostly above 2000 lx while experiencing high air temperatures throughout the measurement days. The analysis indicated that 19 % was above 2000 lx and thermally unacceptable. This could be justified in terms of solar gain and thermal conductivity of clear glass. The room failed to provide a noticeable percentage with illuminance between 300-600 lx and thermally acceptable, however, it demonstrated thermally acceptable conditions around 23 % when illuminance levels were above 600 lx, which only occurred during morning times before 11am. Finally, to summarize the main outcomes from the field measurements, Table 4 demonstrates the potential of each strategy in this research.

Table 4: Summary of environmental conditions in three rooms.

| Environmental Factors | | | Reference Room | | Liquid Glass Coating | | Responsive Blinds | |
|---|---|---|---|---|---|---|---|---|
| | | | 1m | 1.5m | 1m | 1.5m | 1m | 1.5m |
| Daylight 7am -7pm | | Max | 17345 lx | 14925 lx | 5061 lx | 4289 lx | 646 lx | 588 lx |
| | | Average | 4729 lx | 3353 lx | 1567 lx | 1324 lx | 412 lx | 375 lx |
| | | Min | 18.12 lx | 15.06 lx | 15.80 lx | 13.78 lx | 0.00 lx | 0.00 lx |
| | Illuminance Percentages (%) | < 300 | 9.85 % | 12.02 % | 17.93 % | 20.23 % | 24.18 % | 27.83 % |
| | | >300 - <500 | 4.16 % | 5.13 % | 11.49 % | 11.49 % | 29.40 % | 44.94 % |
| | | >500- <600 | 1.38 % | 2.08 % | 2.00 % | 2.07 % | 29.40 % | 27.23 % |
| | | >600 | 84.60 % | 80.77 % | 68.51 % | 66.21 % | 10.82 % | 0.00 % |
| | | >1000 | 78.41 % | 73.19 % | 55.86 % | 51.03 % | 0.00 % | 0.00 % |
| | | >2000 lx | 59.73 % | 52.10 % | 27.13 % | 23.68 % | 0.00 % | 0.00 % |
| | Difference = Sensor 1 – Sensor 2 | | | | | | | |
| | | Max | 6415.80 lx | | 1274.58 lx | | 57.67 lx | |
| | | Average | 1375.38 lx | | 242.98 lx | | 36.71 lx | |
| | | Min | 3.06 lx | | 2.02 lx | | 0.00 lx | |
| Air Temperature 24 hours | | Max | 30.50 °C | | 28.68 °C | | 28.51 °C | |
| | | Average | 26.97 °C | | 26.43 °C | | 26.27 °C | |
| | | Min | 24.36 °C | | 22.96 °C | | 23.58 °C | |
| | Percentage (%) | 22°C -25°C | 20.38 % | | 27.77 % | | 33.33% | |
| | | 26°C - 28°C | 69.44 % | | 72.23 % | | 66.67 % | |
| | | > 28°C | 20.83 % | | 2.78 % | | 5.56 % | |
| | Difference = Outdoor Air Temperature – Indoor Air Temperature in Tested Rooms | | | | | | | |
| | | Max | 4.68 °C | | 6.01 °C | | 6.06 °C | |
| | | Average | 1.15 °C | | 1.69 °C | | 1.85 °C | |
| | | Min | -1.36 °C | | -2.22 °C | | -1.31 °C | |
| | Difference = Controlled Room (°C) – Tested rooms (°C) | | | | | | | |
| | | Max (°C) | - | | 3.42 | | 2.86 | |
| | | Average (°C) | - | | 0.54 | | 0.70 | |
| | | Min (°C) | - | | -0.93 | | -0.08 | |

### *3.3.4 Economic analysis of daylighting strategies*

The economic value of different strategies was conducted by performing the life cycle cost analysis which compared the initial cost and operation cost of different strategies. The initial cost included the cost of material and workmanship installation. The operation cost included the cost of maintenance, service (e.g., cleaning), and replacement if needed. The salvage cost is the cash inflow after selling off the system. In the case of the liquid glass coating, there is no salvage cost because the system is fixed directly onto the glass and cannot be sold. The liquid glass coating has 15 years guarantee and therefore, 15 years was considered in all strategies as the whole life cycle for comparison purposes. The present worth of the operation cost is considered in the evaluation. The following equation (Remer & Nieto, 1995) was used to determine the present value assuming a 6 % interest rate:

$$P = F.(1 + i)^{-n}$$

Where P is the present value or cost, F is the future cost estimated, i is the interest rate, and n is the duration or years.

Table 5 shows the results of the life cycle cost of different strategies. The outcomes indicated that although the strategy of responsive blinds has a much lower initial cost, it has more operation and maintenance costs during the whole life cycle of the product. Therefore, the strategy with liquid glass coating showed to be more economically viable compared to other strategies, the difference between liquid glass coating and responsive blinds is about 18 % in value. The results also showed the cost of each system per square meter (window's area = 2.4 x 3.2m), which considers useful to determine the cost if any system is used in other buildings with different opening areas.

Table 5: Life cycle cost analysis of different strategies.

| | Liquid Glass Coating | | Responsive Blinds | | Integrated Strategy (Liquid Glass Coating + Responsive Blinds) | |
|---|---|---|---|---|---|---|
| | Estimated Cost (RM) | Present Cost (RM) | Estimated Cost (RM) | Present Cost (RM) | Estimated Cost (RM) | Present Cost (RM) |
| **Material** | 4000.00 | 4000.00 | 575.00 | 575.00 | 4575.00 | 4575.00 |
| **Installation** | 400.00 | 400.00 | 600.00 | 600.00 | 1000.00 | 1000.00 |
| **Total Initial Cost** | | **4,400.00** | | **1,175.00** | | **5575.00** |
| **Service (15 years)** | 7500.00 | 3129.49 | 15000.00 | 6258.98 | 18000.00 | 7510.77 |
| **Replacement in 5 years** | | | 1175.00 | 878.03 | 1,175.00 | 878.03 |
| **Salvage value** | | | -150.00 | -112.09 | -150.00 | -112.09 |
| **Replacement in 10 years** | | | 1,175.00 | 656.11 | 1175.00 | 656.11 |
| **Salvage value** | | | -150.00 | -83.76 | -150.00 | -83.76 |
| **Replacement in 15 years** | | | 1175.00 | 490.29 | 1175.00 | 490.29 |
| **Salvage value** | | | -150.00 | -62.59 | -150.00 | -62.59 |
| | | | | | | |
| **Total** | | **7529.49** | | **9199.97** | | **14851.76** |
| **Cost per square metres** | | 980.40 | | 1197.91 | | 1933.82 |

*All values are presented in Malaysian Ringgit (RM). Utilising a foreign currency such as US Dollars, an exchange rate of RM1 = $0.22 can be applied.

## 4. Conclusions

The investigated daylighting techniques demonstrated efficient environmental solutions in an office building in the tropics. The performance of static and responsive strategies revealed new findings that are key to improving indoor environmental conditions. The main findings and contributions are summarised below:

- The application of liquid glass coating exhibited potential and limitations to control and diffuse daylight levels. The strategy effectively managed to cut extreme daylight levels from windows with 6mm clear glass. However, the classification of light quantity in the centre of the room showed that only 11.49 % was between 300 lx and 500 lx, 51.03 % was above 1000 lx and 23.68 % was above 2000 lx. DGP analysis presented imperceptible values except at 3pm that was intolerable with 66.26 %. On the other hand, the study revealed the potential of using liquid glass coating to improve indoor thermal conditions. The results showed that indoor air temperatures experienced a maximum reduction of 3.42 °C which provided a tolerable thermal environment for a room with passive conditions.
- The implementation of responsive blinds using closed-loop protocol was successful in controlling daylight levels in the centre of the room with 100 % below 600 lx while maintaining 45 % of illuminance levels between 300 lx and 500 lx. Moreover, DGP analysis provided imperceptible values for all times except at 3pm that was intolerable with 48.06 %. At the same time, the strategy helped to improve indoor thermal conditions. The findings indicated that with the implementation of the system, the room managed to reduce 2.86 °C which provided a tolerable thermal environment for a room with passive conditions.
- The new integration between liquid glass coating and responsive blinds indicated that the system is capable to control daylight and lower the percentages of DGP which constantly provided imperceptible values. The findings showed that the new integration provided an acceptable daylight distribution and maintain daylight levels between 300 lx and 600 lx.

Generally, these strategies provided technical solutions for retrofitting office buildings with no external shading devices. These strategies offer efficient solutions that are cost-effective and no changes are required for windows and external building façades. However, there were some limitations with this study which only investigated a specific scope. The study did not examine advanced daylight distribution, thermal comfort, user perception and energy consumption.

Therefore, the study recommends future investigations in the tropics. First, there is a need to conduct a full-year study to assess the functionality of tested strategies with different orientations. Second, there is a need to examine the integration of tested strategies via field measurements with different office spaces. Third, the possibilities to investigate adaptive solutions by considering user interaction or by comparing responsive blinds with different control parameters. Finally, future research needs to experiment with the implementation of the Internet of things (IoT) to improve energy efficiency and monitor indoor environmental conditions.

## Acknowledgement

This research was supported by UM Living Lab Grant Programme – Sustainability Science (project no. LL017-16SUS).

## References

Achten, H. (2011). Degrees of Interaction. In Proceedings of 29th eCAADe Conference. pp. 565–572.

Al-Masrani, S. M., Al-Obaidi, K. M., Zalin, N. A., & Isma, M. A. (2018). Design optimisation of solar shading systems for tropical office buildings: Challenges and future trends. *Solar Energy*, *170*, 849-872.

Al-Masrani, S. M., & Al-Obaidi, K. M. (2019). Dynamic shading systems: A review of design parameters, platforms and evaluation strategies. *Automation in construction*, *102*, 195-216.

Al-Obaidi, K. M., Ismail, M., & Rahman, A. M. A. (2014). Design and performance of a novel innovative roofing system for tropical landed houses. *Energy Conversion and Management*, *85*, 488-504.

Al-Obaidi, K. M., Munaaim, M. A. C., Ismail, M. A., & Rahman, A. M. A. (2017). Designing an integrated daylighting system for deep-plan spaces in Malaysian low-rise buildings. *Solar Energy*, *149*, 85-101.

ASHRAE. Weather Data Viewer 2021. Region-Southwest Pacific WMO Region 5—Malaysia. Available online: https://www.ashrae.org/technical-resources/bookstore/weather-data-center#weather (accessed on 15 June 2022).

Bahdad, A. A. S., Fadzil, S. F. S., Onubi, H. O., & BenLasod, S. A. (2021). Sensitivity analysis linked to multi-objective optimization for adjustments of light-shelves design parameters in response to visual comfort and thermal energy performance. *Journal of Building Engineering*, *44*, 102996.

Bahdad, A. A. S., Syed Fadzil, S. F., Onubi, H. O., & BenLasod, S. A. (2022). Balancing daylight in office spaces with respect to the indoor thermal environment through optimization of light shelves design parameters in the tropics. *Indoor and Built Environment*, 1420326X221086537.

Cannavale, A., Ayr, U., Fiorito, F., & Martellotta, F. (2020). Smart electrochromic windows to enhance building energy efficiency and visual comfort. *Energies*, *13*(6), 1449.

CIBSE, E. D. (2015). CIBSE Guide a, Chart. *Inst. Build. Serv. Eng. London*.

Chaiwiwatworakul, P., & Chirarattananon, S. (2013). A double-pane window with enclosed horizontal slats for daylighting in buildings in the tropics. *Energy and Buildings*, *62*, 27-36.

Chaloeytoy, K., Ichinose, M., & Chien, S. C. (2020). Determination of the Simplified Daylight Glare Probability (DGPs) Criteria for Daylit Office Spaces in Thailand. *Buildings*, *10*(10), 180.

Chiesa, G., Di Vita, D., Ghadirzadeh, A., Herrera, A. H. M., & Rodriguez, J. C. L. (2020). A fuzzy-logic IoT lighting and shading control system for smart buildings. *Automation in construction*, *120*, 103397.

Chirarattananon, S., Chaiwiwatworakul, P., & Patanasethanon, S. (2003). Challenges of daylighting with the luminosity and variability of the tropical sky. *Lighting Research & Technology*, *35*(1), 3-10.

Davila, C. B., & Fiorito, F. (2021). On the combined use of laser-cut panel light redirecting systems and horizontal blinds for daylighting and solar heat control, a focus on visual comfort objectives. *Solar Energy*, *230*, 186-194.

Day, J. K., Futrell, B., Cox, R., Ruiz, S. N., Amirazar, A., Zarrabi, A. H., & Azarbayjani, M. (2019). Blinded by the light: Occupant perceptions and visual comfort assessments of three dynamic daylight control systems and shading strategies. *Building and Environment*, *154*, 107-121.

de Vries, S. B., Loonen, R. C., & Hensen, J. L. (2021). Multi-state vertical-blinds solar shading–Performance assessment and recommended development directions. *Journal of Building Engineering*, *40*, 102743.

Do, C. T., & Chan, Y. C. (2021). Daylighting performance analysis of a facade combining daylight-redirecting window film and automated roller shade. *Building and Environment*, *191*, 107596.

Do, C. T., & Chan, Y. C. (2020). Evaluation of the effectiveness of a multi-sectional facade with Venetian blinds and roller shades with automated shading control strategies. *Solar energy*, *212*, 241-257.

Fathoni, A. M., Chaiwiwatworakul, P., & Mettanant, V. (2016). Energy analysis of the daylighting from a double-pane glazed window with enclosed horizontal slats in the tropics. *Energy and Buildings*, *128*, 413-430.

García-Solórzano, L. A., Esparza-Lopez, C. J., & Al-Obaidi, K. M. (2020). Environmental design solutions for existing concrete flat roofs in low-cost housing to improve passive cooling in western Mexico. *Journal of Cleaner Production*, *277*, 123992.

Hammad, F., & Abu-Hijleh, B. (2010). The energy savings potential of using dynamic external louvers in an office building. *Energy and Buildings*, *42*(10), 1888-1895.

Hashemi, A. (2014). Daylighting and solar shading performances of an innovative automated reflective louvre system. *Energy and Buildings*, *82*, 607-620.

Huo, H., Xu, W., Li, A., Lv, Y., & Liu, C. (2021). Analysis and optimization of external Venetian blind shading for nearly zero-energy buildings in different climate regions of China. *Solar Energy*, *223*, 54-71.

Huang, T. Y., Hocheng, H., Chou, T. H., & Yang, W. H. (2013). Bring free light to buildings: overview of daylighting system. *Materials and processes for energy: communicating current research and technological developments. Formatex Research Center*.

Ismail M. (2010). The potential of hybrid turbine ventilator to improve indoor climatic conditions in hot-humid environment [Ph.D. thesis]. Universiti Sains Malaysia.

Iwata, T., Taniguchi, T., & Sakuma, R. (2017). Automated blind control based on glare prevention with dimmable light in open-plan offices. *Building and Environment*, *113*, 232-246.

Karanouh, A., & Kerber, E. (2015). Innovations in dynamic architecture. *Journal of Facade Design and Engineering*, *3*(2), 185-221.

Kazanasmaz, T. (2013). Fuzzy logic model to classify effectiveness of daylighting in an office with a movable blind system. *Building and Environment*, *69*, 22-34.

Kim, D., Cox, S. J., Cho, H., & Yoon, J. (2018). Comparative investigation on building energy performance of double skin façade (DSF) with interior or exterior slat blinds. *Journal of Building Engineering*, *20*, 411-423.

Kleindienst, S., & Andersen, M. (2009). The adaptation of daylight glare probability to dynamic metrics in a computational setting. In *Proceedings of Lux Europa 2009–11th European lighting conference* (No. CONF).

Kolodziej, P., & Rak, J. (2013). Responsive building envelope as a material system of autonomous agents.

Konstantoglou, M., & Tsangrassoulis, A. (2016). Dynamic operation of daylighting and shading systems: A literature review. *Renewable and Sustainable Energy Reviews*, *60*, 268-283.

Ko, W. H., Schiavon, S., Brager, G., & Levitt, B. (2018). Ventilation, thermal and luminous autonomy metrics for an integrated design process. *Building and Environment*, *145*, 153-165.

Kristalbond. (2022). Liquid Glass Coating. https://www.kristalbond.com/case-study, Accessed date: 15 June 2022.

Kunwar, N., Cetin, K. S., Passe, U., Zhou, X., & Li, Y. (2020). Energy savings and daylighting evaluation of dynamic venetian blinds and lighting through full-scale experimental testing. *Energy*, *197*, 117190.

Kwong, Q. J. (2020). Light level, visual comfort and lighting energy savings potential in a green-certified high-rise building. *Journal of Building Engineering*, *29*, 101198.

Lee, J. H., Jeong, J., & Chae, Y. T. (2020). Optimal control parameter for electrochromic glazing operation in commercial buildings under different climatic conditions. *Applied Energy*, *260*, 114338.

Lim, G. H., Hirning, M. B., Keumala, N., & Ghafar, N. A. (2017b). Daylight performance and users' visual appraisal for green building offices in Malaysia. *Energy and Buildings*, *141*, 175-185.

Lim, Y. W., Kandar, M. Z., Ahmad, M. H., Ossen, D. R., & Abdullah, A. M. (2012). Building façade design for daylighting quality in typical government office building. Building and Environment, 57, 194-204.

Lim, Y. W., & Heng, C. Y. S. (2016). Dynamic internal light shelf for tropical daylighting in high-rise office buildings. *Building and Environment*, *106*, 155-166.

Liu, X., Sun, Y., Wei, S., Meng, L., & Cao, G. (2021). Illumination distribution and daylight glare evaluation within different windows for comfortable lighting. *Results in Optics*, *3*, 100080.

Luo, Z., Sun, C., & Dong, Q. (2020). A daylight-linked shading strategy for automated blinds based on model-based control and Radial Basis Function (RBF) optimization. *Building and Environment*, *177*, 106854.

MALAYSIAN STANDARD. (2017). Energy efficiency and use of renewable energy for non-residential buildings – Code of practice. Kuala Lumpur: Department of Standards Malaysia.

Mardaljevic, J., Andersen, M., Roy, N., & Christoffersen, J. (2012). Daylighting metrics: is there a relation between useful daylight illuminance and daylight glare probabilty?. In *Proceedings of the building simulation and optimization conference BSO12* (No. CONF).

Mayhoub, M. S. (2014). Innovative daylighting systems' challenges: A critical study. *Energy and buildings*, *80*, 394-405.

Mettanant, V., & Chaiwiwatworakul, P. (2014). Automated vertical blinds for daylighting in tropical region. *Energy Procedia*, *52*, 278-286.

Mukherjee, S., Birru, D., Cavalcanti, D., Shen, E., Patel, M., Wen, Y. J., & Das, S. (2010). Closed loop integrated lighting and daylighting control for low energy buildings. *Proceedings of the 2010 ACEEE*, 252-269.

Nabil, A., & Mardaljevic, J. (2006). Useful daylight illuminances: A replacement for daylight factors. *Energy and buildings*, *38*(7), 905-913.

Nezamdoost, A., Van Den Wymelenberg, K., & Mahic, A. (2018). Assessing the energy and daylighting impacts of human behavior with window shades, a life-cycle comparison of manual and automated blinds. *Automation in Construction*, *92*, 133-150.

Olbina, S., & Hu, J. (2012). Daylighting and thermal performance of automated split-controlled blinds. *Building and Environment*, *56*, 127-138.

Ong, K. S. (2011). Temperature reduction in attic and ceiling via insulation of several passive roof designs. *Energy Conversion and Management*, *52*(6), 2405-2411.

Qahtan, A., Keumala, N., Rao, S. P., & Abdul-Samad, Z. (2011). Experimental determination of thermal performance of glazed façades with water film, under direct solar radiation in the tropics. *Building and Environment*, *46*(11), 2238-2246.

Reinhart, C. F., & Voss, K. (2003). Monitoring manual control of electric lighting and blinds. *Lighting research & technology*, *35*(3), 243-258.

Remer, D. S., & Nieto, A. P. (1995). A compendium and comparison of 25 project evaluation techniques. Part 1: Net present value and rate of return methods. *International Journal of Production Economics*, 42(1), 79-96.

Sharaidin, K. (2014). *Kinetic facades: towards design for environmental performance* (Doctoral dissertation, RMIT University).

Shin, H. Y., Kim, G., & Kim, J. T. (2013). Effect of occupants' behaviour of daylight controls on residential visual environment. *Indoor and Built Environment*, *22*(1), 191-202.

Somasundaram, S., Thangavelu, S. R., & Chong, A. (2020). Improving building efficiency using low-e coating based retrofit double glazing with solar films. *Applied Thermal Engineering*, *171*, 115064.

Sun, Y., Wilson, R., & Wu, Y. (2018). A Review of Transparent Insulation Material (TIM) for building energy saving and daylight comfort. *Applied energy*, *226*, 713-729.

Tabadkani, A., Roetzel, A., Li, H. X., Tsangrassoulis, A., & Attia, S. (2021). Analysis of the impact of automatic shading control scenarios on occupant's comfort and energy load. *Applied energy*, *294*, 116904.

Tang, C. K., & Chin, N. (2013). Building energy efficiency technical guideline for passive design. Public Works Department Malaysia, Kuala Lumpur.

Tian, Z., Lei, Y., & Jonsson, J. C. (2019, February). Daylight luminous environment with prismatic film glazing in deep depth manufacture buildings. In *Building Simulation* (Vol. 12, No. 1, pp. 129-140). Tsinghua University Press.

Tian, Z., Lin, P., He, Y., & Jonsson, J. C. (2021). A study of luminous environment with prism daylight redirecting fenestrations in classrooms. *Indoor and Built Environment*, *30*(4), 461-475.

Wienold, J., & Christoffersen, J. (2006). Evaluation methods and development of a new glare prediction model for daylight environments with the use of CCD cameras. *Energy and buildings*, *38*(7), 743-757.

Wienold, J. (2007, September). Dynamic simulation of blind control strategies for visual comfort and energy balance analysis. In *Building Simulation* (pp. 1197-1204). Beijing, China: IBPSA.

Wu, H., & Zhang, T. (2022). Optimal Design of Complex Dynamic Shadings: towards Sustainable Built Environment. *Sustainable Cities and Society*, 104109.

Xie, J., & Sawyer, A. O. (2021). Simulation-assisted data-driven method for glare control with automated shading systems in office buildings. *Building and Environment*, *196*, 107801.

Zhao, B., Wang, C., Hu, M., Ao, X., Liu, J., Xuan, Q., & Pei, G. (2022). Light and thermal management of the semi-transparent radiative cooling glass for buildings. *Energy*, *238*, 121761.

**Highlights:**

- Static and responsive daylighting strategies were experimentally investigated.
- The tested strategies provided effective solutions to control daylight levels.
- The proposed daylighting systems improved thermal conditions.
- The integrated daylighting system presented a responsive environmental strategy.

**Declaration of interests**

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

## Author Statement

**Karam M. Al-Obaidi:** Conceptualization, Methodology, Supervision, Formal analysis, Software, Validation, Visualization, Writing- Original draft preparation, Writing- Reviewing and Editing. **Husam S. Al-Duais**: Investigation, Resources, Data curation, Methodology, Validation, Writing- Original draft preparation. **Nayef A.M. Alduais:** Methodology, Software, Investigation, Data curation, Visualization, Validation, Resources, Writing- Original draft preparation. **Ali Alashwal***:* Conceptualization, Methodology, Supervision, Resources, Formal analysis, Project administration, Funding acquisition, Writing- Original draft preparation. **Muhammad Azzam Ismail**: Conceptualization, Methodology, Supervision, Project administration, Funding acquisition, Writing- Original draft preparation.