Advanced parametric louver systems with bi-axis and two-layer designs for an extensive daylighting coverage in a deep-plan office room.

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ABSTRACT

Advanced daylighting systems have become commonly used in modern architecture for a more sustainable environment. The mainstream of recent daylighting studies focuses not only on the quantity but also the quality of daylight delivered to an interior space. The more uniform daylight is distributed in the required illuminance range, the more light stability is achieved, and the longer time is illuminated by daylight, the more electrical lighting energy can be potentially saved. This study proposes an advanced daylighting design based on a parametrically controlled louver with reflective slats to redirect sunlight onto a ceiling, which can then serve as a source of diffuse light to illuminate a room. The design aims to achieve steadier and more uniform daylight distribution during the working hours in a deep-plan office room. The angle of each slat of the louver is parametrically controlled to target a corresponding area on the ceiling. In order to achieve a steadier daylighting, a bi-axis design and a two-layer design with a shifted target are evaluated and compared with a one-axis design. A daylighting analysis of the proposed design is exemplified for a south-oriented 8m deep office room in a hot arid territory. The daylight analysis was performed using Grasshopper software as a parametric tool to link with Radiance and DAYSIM daylighting analysis. The proposed design shows promising merit that it can provide a relatively steady and

distributed daylight coverage for more than 90% of the floor area within the recommended acceptable range 300~500 lux during the working hours.

Keywords: Parametric louver, One-axis, Bi-axis & Two-layer, Percentage daylight coverage, Deep-plan office, Grasshopper

1 Introduction

1.1 Background

Daylight is an important role in our life that influences all species on the planet. Even architecture as an inanimate is strongly affected by daylight from different aspects such as design, shape, function, orientation and mass; and in some cases, the architecture may respond to climate changes and sun movement. Some species can adapt to climate changes by changing their phases in order to survive, likewise, architects are inspired by the climatic adaptation of these species to create more sustainable architecture. One of the interesting plants known as heliotrope (Henriques et al., 2012), can react and respond to the sun movement whenever the sun moves, in order to receive as much solar radiation as possible. Modern architecture can use this heliotropic response to optimize the use of daylight to save energy. Therefore, daylight in architecture is one of the crucial sources for energy-saving and achieving passive building (Boubekri, 2008). Several generic elements are used in architecture to adapt with climate changes such as windows (Xue et al., 2014), shadings (Dubois, 2001), fenestration systems (El Daly, 2014), automated systems (Hammad and Abu-Hijleh, 2010; Lee et al., 1998; Nielsen et al., 2011), concentrating systems (Li et al., 2018) and bioclimatic daylighting systems (Mayhoub, 2014). A combination of these elements can be engaged together to maximise the use of daylight (Al-Obaidi et al., 2017; Hashemi, 2014; Park et al., 2014).

In the recent 30 years, solar concentrating technologies (Li et al., 2020) and daylighting systems (Mayhoub, 2019) have been improved in order to enhance daylighting in the deep interior of a building (Baker and Steemers, 2014). Daylighting systems can be static (Littlefair, 1996; Littlefair et al., 1994) or dynamic elements located onto or near a building’s façade to collect and redirect daylight into the building to improve daylighting performance and save energy (Eltaweel et al., 2020;

Konstantoglou and Tsangrassoulis, 2016). Generally, there are many types of daylighting systems which can be divided into three main categories; light guiding systems, light transporting system (Tsangrassoulis, 2008) and fenestration systems. A light-guiding system can reflect and redirect sunlight into deep interior of a room, whereas, a light transporting system uses a different process, which is more complicated; by using a collector device to collect the light, then transport it in specific reflectors, and finally distribute it inside the room.

A light-guiding system is often mounted at the upper part of a typical window and uses a static device such as light shelf (Meresi, 2016), optical louver system (Konis and Lee, 2015), compound parabolic concentrator panel (Xuan et al., 2019) and prismatic panel (Mashaly et al., 2017). These well-known daylighting systems can reflect sunlight into a deep plan room; however, the reflected light over the ceiling is often neither uniform nor steady due to their static state comparing to the dynamic state of sunlight, and accordingly daylight distribution in the room is not uniform and unsteady. In addition, they may have some drawbacks such as time limitations of daylight provided, risk of glare or excessive light and high contrast of light, which probably lead to visual discomfort for occupants.

1.2 Critical discussion

Windows are the primary element in architecture and considered as a fenestration system; they are used on the outer skin of the buildings to protect from weather changes, provide daylight, transmit solar radiation for passive heating and simultaneously remain the visual interaction between the indoor and outdoor (Fasi and Budaiwi, 2015). Energy performance inside the building can vary based on window fenestration type (Orouji et al., 2019). In particular, the efficient use of solar radiation through the window as a source of natural daylight to the building should have a significant effect on the occupants (Boubekri, 2008; Li et al., 2005). For efficient control of daylight, advanced or smart windows can be used to control the penetration of daylight into the buildings. Smart windows can be defined by several factors such as the optical properties, tinting, heat transfer coefficient, durability, switching times, etc. Dynamic solution like adaptive windows have the ability to adjust their optical properties in response to the ambient conditions, and therefore can improve the energy performance and user’s comfort (Tällberg et al., 2019).

These types of windows are usually called “smart windows”, which can be divided into several categories such as thermochromic, photochromic, electrochromic, liquid crystals and suspended-particle glazings (Baetens et al., 2010). Electrochromic and thermochromic glazing as advanced types of fenestration systems can efficiently control the sunlight transmittance to the room (Granqvist, 2016). Use of electrochromic and thermochromic glazing will be also considered in the current study in addition to the parametric louver.

Electrochromic glazing is a switchable window (Granqvist et al., 2018), capable to disperse the daylight through its translucency character, which can be controlled automatically by applying a low electrical voltage between a double glazing system (Lee et al., 2006). It can adapt its optical properties from a clear state to a fully coloured sate through different type of stimuli such as gas concentration and applied voltage (Dussault and Gosselin, 2017). It has been found that electrochromic window can significantly reduce the energy consumption inside the building in warmer climates, due to reduced solar heat gain (Mäkitalo, 2013). It can be also used for privacy. This control flexibility of electrochromic glazing can efficiently reduce the solar heat gains, disperse the daylight and limit the glare inside the building zone, and simultaneously, provide visual contact to the outside regardless of their coloured states (Jelle et al., 2012).

Differently, thermochromic glazing is based on the colour change of a material with temperature. Accordingly, it can adjust its transmittance to reduce the intensity level of the penetrated light in response to temperature change when solar radiation is strong (Parkin et al., 2008). G-value of thermochromic window vary between 0.62 and 0.2 for the clearest state and between 0.449 and 0.1 for the darkest state (Tällberg et al., 2019). Thermochromic glazing techniques are considered a promising technology for the next generation of architectural windows. Thermochromic system can be used in a shape of film, coating and glazing. One type of thermochromic coating is mainly based on vanadium oxide (VO_2), which can transform from a semiconducting to metallic state (Aburas et al., 2019). These states are referred to “light and dark” states, respectively, while the former is relatively transparent to infrared radiation and the latter is opaque to such radiation (Ye et al., 2012). The advantage of this material is that its changeable process is highly reversible.

Venetian blinds have been widely used in office buildings as shading devices to protect from direct sunlight and in some cases to control the penetration of daylight inside the room, which needs regular manual control. However, manual control is more or less efficient depending on users' behaviour. Incorporating automation control with the Venetian blinds can dramatically increase its performance as a thermal and visual comfort for occupants (Tian et al., 2014). A recent study proposed an automated shading system which can entirely track the sun movement in a three axes rotation to optimize the use of daylight and protect from glare for visual comfort (Chi et al., 2020). As a critical point of view, this system can only prevent the penetration of sunlight into the room, while the provision of natural daylight is still limited. On the other hand, our previous studies proposed an automated louver system which tracks the sun movement and reflects the sunlight to the deep-plan room (Eltaweel and Su, 2017a, d), and simultaneously controls the level of daylight illuminance. However, the rotation of this louver system can only track sun altitude, which influences the amount of daylight provision accordingly, achieving 50 – 70% of daylight coverage at its best performance (Eltaweel and Su, 2017b).

1.3 Aim of this study

The current study investigates an innovative louver system that can entirely track the sun movement during the daytime, protect from direct sunlight, and provide steadier and well-distributed daylight for visual comfort. Together with electrochromic and thermochromic glass, the automated louver system can accurately control and optimise the penetration of daylight inside the building, which can achieve up to 90% of daylight coverage during the working hours. The whole system is connected and controlled by using parametric design aiming to achieve more uniform and steadier daylight distribution in the deep-plan room. In order to achieve this aim, both solar altitude and azimuth are respected simultaneously by using bi-axis and two-layer rotation methods. Moreover, the intensity and transmission of daylight is controlled by the use of smart glazings. The new proposed systems represent innovative, algorithmic methods using parametric controls to maximize the amount of natural daylight.

2 Hypothesis

This study proposes an advanced louver system controlled parametrically to respond to the sun movement. Reflective slats are rotated parametrically using Grasshopper based on Rhinoceros 3D, and these mirrored louvers are used to reflect the direct sunlight onto the ceiling of a deep-plan office room, and then the illuminated ceiling acts as a source of light to the room. The main concept is to keep the reflected sunlight towards fixed target points on the ceiling during the daytime, and consequently, keep the daylight distribution uniform in the room. In architecture, the character of most surfaces has diffused reflection (Serra, 1998). Thus, this behaviour tends to distribute natural light more uniformly inside the interior spaces. Moreover, it is important to keep the distributed daylight within the accepted range for visual comfort (Hernández et al., 2017) and control the occupants' interaction with the window shadings (Van Den Wymelenberg, 2012); therefore, transmittance switchable windows should be used to adjust the interior daylight illumination levels according to the varying intensity of solar radiation.

Along with the parametric louver, electrochromic and thermochromic glazings (Taveres-Cachat et al., 2017) are also applied in this study to control penetration of sunlight. Electrochromic glass (Piccolo and Simone, 2015) is installed at the bottom part of a window and used mainly as a translucent material to provide diffused light and as well control the amount of the provided daylight by using its switchable utility (Fernandes et al., 2013). Thermochromic (Parkin et al., 2008) glass is installed at the upper part of the window, beside the louver, and used as a transparent material to control the intensity of the reflected light coming from the louver system via adjusting the light transmittance by changing its phase based on solar intensity (temperature). Therefore, electrochromic window is responsible for the area near to the window within 2 meters depth, aiming to disperse the direct sunlight and keep the illumination between 300~500 lux. Meanwhile, thermochromic window is responsible to illuminate the area deep inside the room by controlling the intensity level of the reflected light within 300~500 lux.

In order to achieve more uniform and steadier daylight distribution, an automated louver structure, electrochromic window and thermochromic window are connected simultaneously and controlled parametrically. Parametric design as a tool is used to find a compromise between the climatic parameters such as altitude, azimuth, solar intensity, sky conditions and the physical parameters of louver and glass to maintain the provided light within the range 300~500 lux to meet the occupants comfort according to CIE standard (Baker and Steemers, 2014). This study analyses the percentage daylighting coverage within the range 300~500 lux, which is recommended for office applications (Staff, 2004), at the desktop level 0.75 m. General daylighting systems can achieve 17 – 40% of daylight coverage in their best cases (Eltaweel and Su, 2017c) within the accepted range of illumination, however, the proposed daylighting system in our study can achieve 75~95% in various climate conditions throughout the year.

3 Methodology

Computer software is developed orderly to create intricate graphical drawings, and accordingly, parametric software is produced to deal with complex geometries with different parameters (Eltaweel and Su, 2017c). The parametric software, Grasshopper (Davidson, 2020) based on Rhinoceros 3D (Associates, 2017), is a graphical algorithmic editor and capable to control several parameters simultaneously under particular definitions connected in a formula (Rahimzadeh, 2015; Suyoto et al., 2015; Wagdy and Fathy, 2015). This formula defines the model parameters in a flexible way which provides accurate control to manipulate with the whole model (Davidson, 2020). Grasshopper interface is capable of inserting different plugins such as “Honeybee and Ladybug” (McNeel, 2020), which could work as an engine to generate the well-known environmental software Radiance (Mead, 2017), DAYSIM and EnergyPlus (Erlendsson, 2014). Ladybug is used as a gate to provide all weather data of any region, by directly importing the weather file (EPW) of the selected region with sky-type “Climate-based daylight modelling”, then, all weather data of this place should be available and intuitively influences on the model in Grasshopper. Accordingly, the whole model can be manipulated easily by the created formula in Grasshopper to adapt with weather conditions of the selected region. New Cairo in Egypt was selected as a region representing a hot arid territory which can provide direct sunlight almost all the year. Annual hourly data analysis was obtained by climate-based hourly computer simulation for International Airport in Cairo location, which is the closest point to the New Cairo, by using EPW weather file. For daylight hours analysis, the data revealed that the sky is clear, intermediate and overcast during 53%, 37% and 10% of the year, respectively, based on the criteria in Table 1 (Fernandes et al., 2013). That means that direct solar radiation is ~90% available during the year in this location.

Table 1: Definitions of sky types (Fernandes et al., 2013)

CIE sky type	*Condition*
Clear	Direct normal irradiance (DNI) is more than 200% of diffuse horizontal irradiance (DHI)
Intermediate	Direct normal irradiance (DNI) is between 5% and 200% of diffuse horizontal irradiance (DHI)
Overcast	Direct normal irradiacne (DNI) is less than 5% of diffuse horizontal irradiance (DHI)

The proposed system consists of automated mirrored louver with 90% specular reflection, which can rotate parametrically around their axis to adapt with all solar angles wherever the sun moves at any direction. Two different methods were developed to follow the sun movement in all directions based on previous studies (Eltaweel and Su, 2017b, d) aiming to improve the availability of daylight during the daytime, and this part will be discussed in details in the following section.

3.1 Parametric louver systems

The primary concept of the parametric louver is to rotate slats around individual axes in response to the sun movement in order to reflect sunlight towards distributed target points on a ceiling. The parametric louver is attached to the upper part of a window in a 60 cm double-skin façade. The parametric louver starts at 220 cm from the floor level and ends at 30 cm to the ceiling. The parametric louver system is designed to achieve the required daylight illuminance range of 300-500 lux for a duration as long as possible during a day.

3.1.1 One-axis parametric louver system

This type of parametric louver was investigated previously by using mirrored slats with one-axis rotation for each (Eltaweel and Su, 2017d). Such a system was parametrically controlled using an algorithmic formula created in Grasshopper based on Rhinoceros 3D. Further study of the same design (Eltaweel and Su, 2017b) proved that this system can reach approximately 70% of daylight coverage within 300-500 lux in an office room at the desk level throughout the year. Moreover, this system could be improved by adding an advanced window glazing, discussed in Section 3.2. The parametric louver system consists of 10 rows; each row consists of two parts, a rotating slat and a fixed slat, see **Figure 1**. The rotating slats assigned as a mirrored coated surface with 90% reflectivity and they are controlled independently based on solar angles. The rotating slat in each row has a specific rotation angle according to its target point on the ceiling. However, they are all connected simultaneously and controlled parametrically. On the other hand, the fixed slats are assigned as dark matt material and work as shading part to prevent any excessive light passing between the rotating slats, and simultaneously reduce the risk of glare or excessive brightness coming from the window. The rotation process is performed from a hinged axis (X-axis) around the tangent line between two slats, as shown in **Figure 1**. The rotating slat side is 15 cm wide, while the fixed slat is 20 cm and the number of rows assigned to 10 where the distance between two adjacent rows is 14 cm, giving 140cm height of the louver system. Description about the system components, materials and dimensions is shown in **Figure 1.**

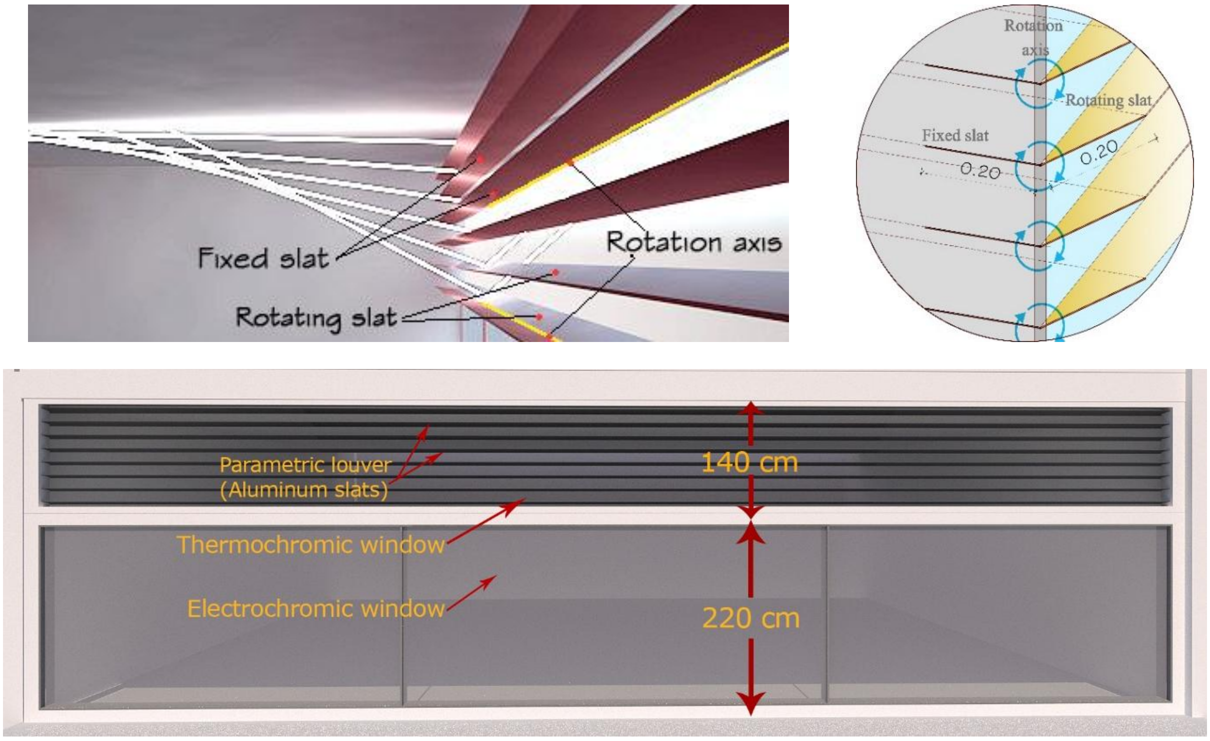


Figure 1: One-axis parametric louver system, cross-section and side-view (top), front view (bottom)

In response to the variation of solar altitude, this one-axis parametric louver rotates slats to reflect sunlight onto the ceiling, which then works as a source of light to illuminate the room (Eltaweel and Su, 2017a). However, one-axis rotation cannot track the variation of solar azimuth, so the illuminated patch of the reflected light on the ceiling will move with time in a longitudinal path as shown in **Figure 2**.

According to the sun movement, the illuminated area for the daylight illuminance range of 300~500 lux should be the maximum when the incidence plane of sunlight is perpendicular to the south-facing façade. However, the illuminated area will become smaller when the sunlight comes from the west or the east. To show such variation, the hours of daylight autonomy on a selected day is given in **Figure 3**. It is clear that one-axis parametric louver can provide more uniform daylight inside the room but still not steady enough at the late and early time of a day.

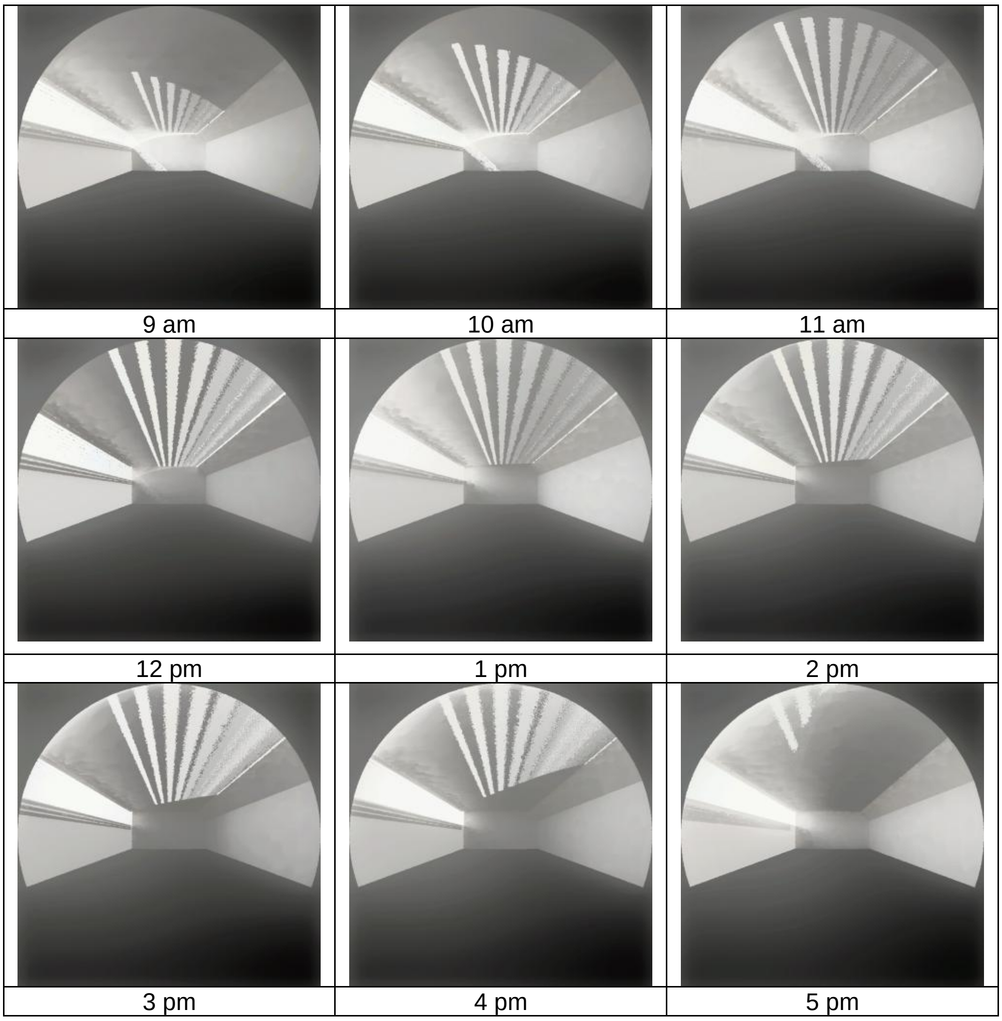


Figure 2. Illuminance maps showing illuminated patches are moving over the ceiling from 9 am to 5 pm on September 21st.

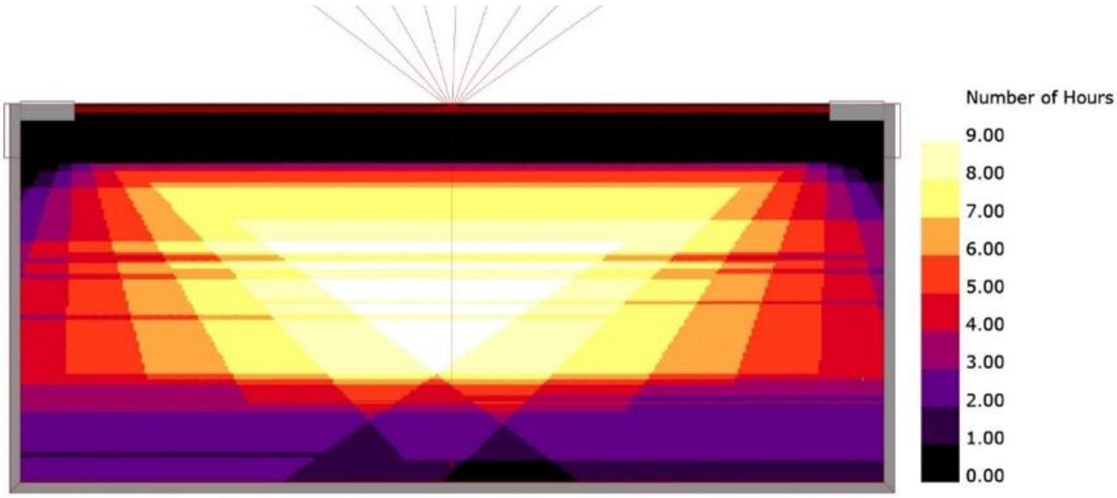


Figure 3. Hours of daylight autonomy for the range of 300-500 lux at the desktop level on the 21st of September.

3.1.2 Bi-axis parametric louver system

Bi-axis louver movement is inspired by Heliotrope planet (Henriques et al., 2012; Ramzy and Fayed, 2011) which can move to respond to the sun movement to collect more light. The bi-axis parametric louver system has its slats to rotate in two directions according to the change in solar altitude and azimuth, so the slats can reflect sunlight towards a set of target points on the ceiling as shown in Figure 4.

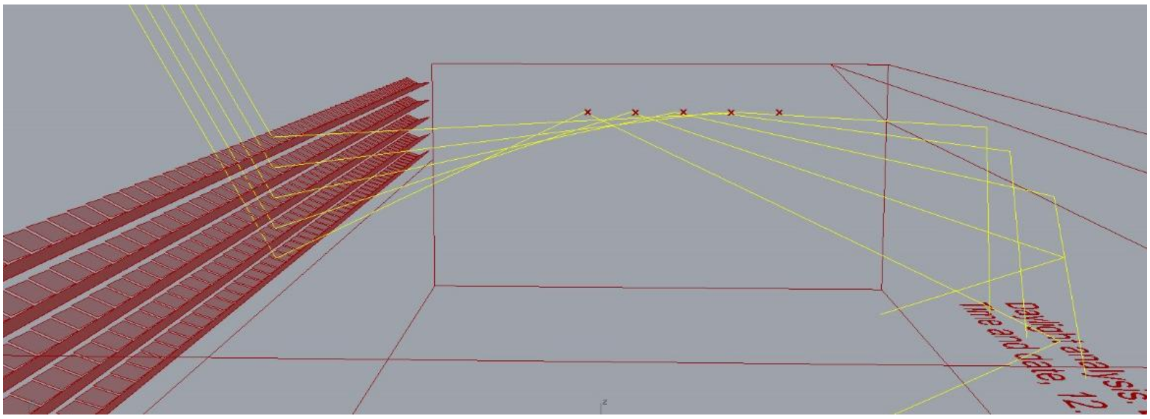


Figure 4: Schematic raytracing study of a bi-axis parametric louver system

Similar to the one-axis parametric louver, the bi-axis louver also includes two parts (rotating part and fixed part); however, its rotating part consists of deployed slats divided into consecutive segments of slats as shown in **Figure 5**. Every slat segment is hinged from one corner where it can rotate in a biaxial rotation from this corner around X and Y pivots, while the opposite corner is fixed with a ball joint on a moveable bar which can control the rotation of the slat segment. The movable bar can move horizontally and vertically to adapt the reflection surface with the sun movement and keep the reflected ray on a fixed target, see Figure 6. The opposite corner serves as a control point for rotation. To obtain a rotation angle (α), the control bar moves on the YZ plane to rotate each slat segment around its X axis. Similarly, the movement of the bar on the XZ plane can cause a rotation of each slat around its Y axis to give a rotation value (β), see Figure 5. Two rotations can be controlled parametrically and simultaneously in modelling by calculating the 3D coordinate values of the control point for the required rotation angles. For more explanation, every single slat can rotate around its X axis with a specific rotation value (α) which responds the altitude of the sun, and simultaneously, this slat can rotate around its Y axis with a specific rotation value (β) which responds the azimuth of the sun. Two rotations are controlled parametrically and connected simultaneously.

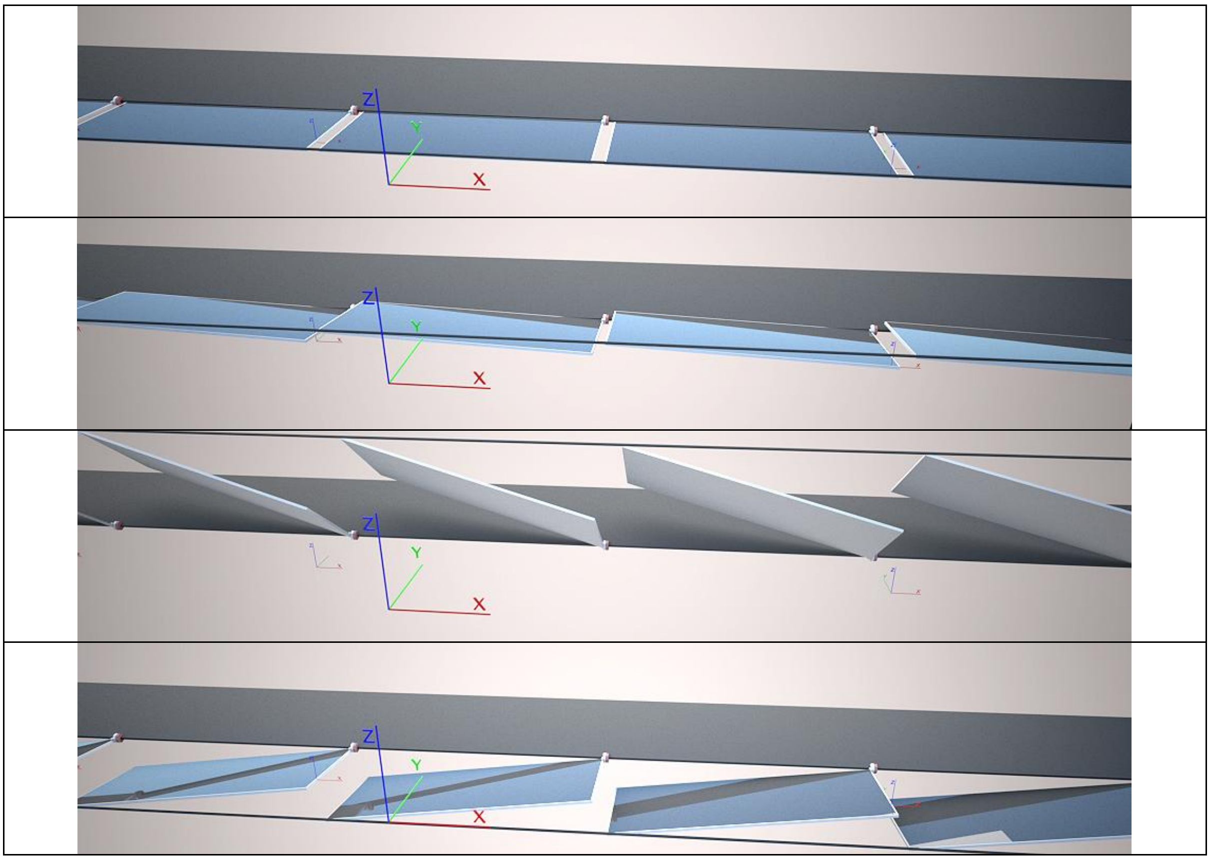


Figure 5: Bi-axis louver rotation by using a movable bar.

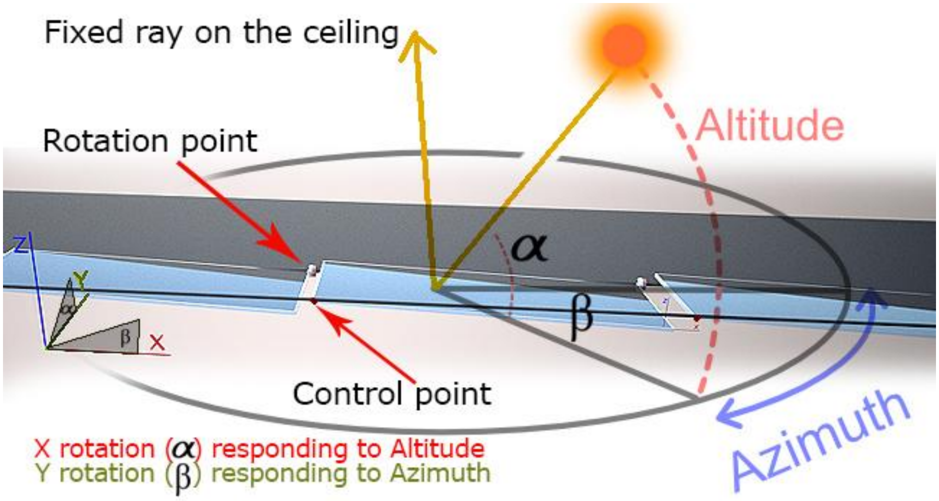


Figure 6: Bi-axis rotation corresponding to solar angles

Technically, every single slat has two rotation angles Beta (β) and Alpha (α), which varies parametrically in a biaxial rotation around its X and Y pivots in the coordinate using a specific algorithmic formula created in Grasshopper, see **Figure 7**. This formula solves the relation between the direction of the reflected ray to the ceiling and the direction of the incident ray from the sun, by using “orientation component” which works as a heliotropic mirror surface between the two rays. Thus, the slat’s angles β and α should alter simultaneously with the solar altitudes and azimuths. Accordingly, the reflected light over the ceiling should be steadier during the daytime, see **Figure 8.**

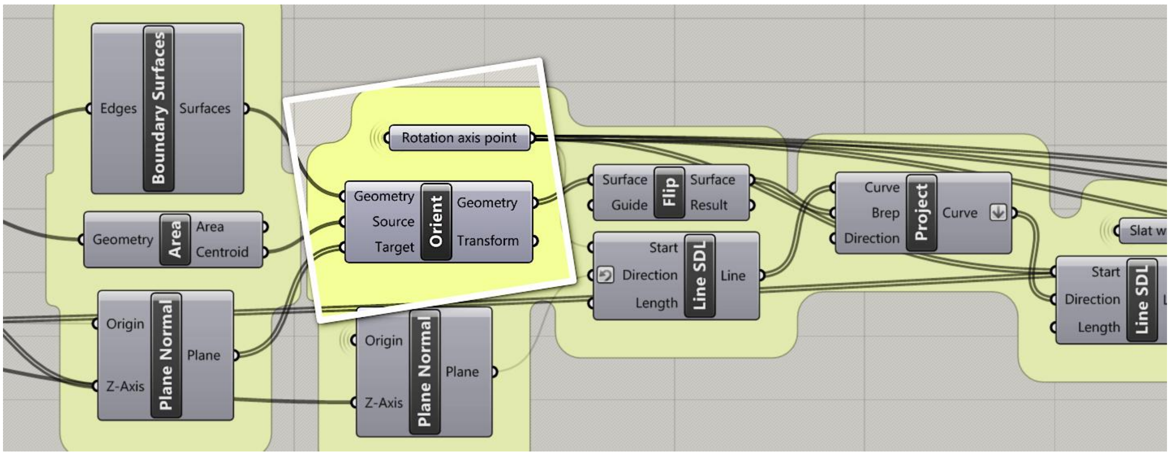


Figure 7: Grasshopper formula to control the rotation angles

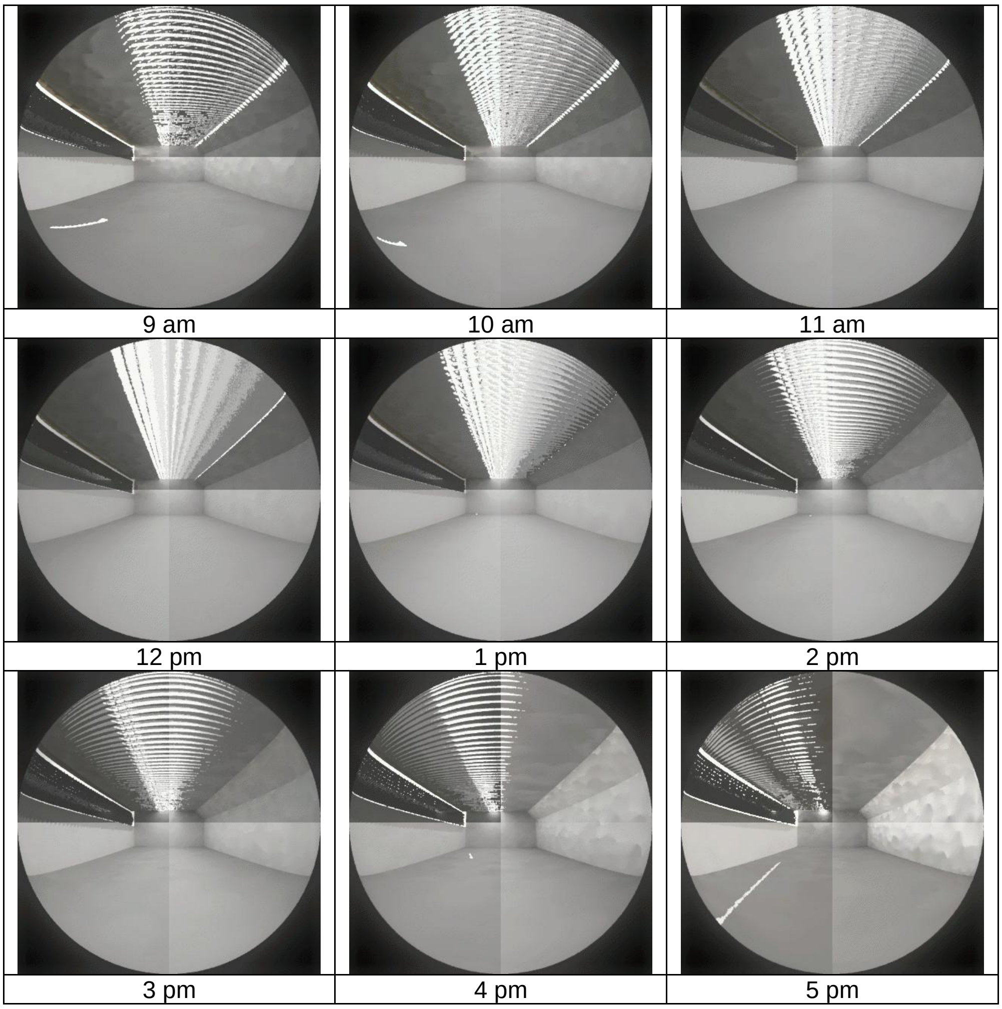


Figure 8: Illuminance maps for the bi-axis parametric louver system from 9 am to 5 pm on September 21st.

3.1.3 Two-layer parametric louver system

This system consists of two sets of rotating slats, one set is deployed horizontally along the façade and can rotate responding to the solar altitude trajectory (Eltaweel and Su, 2017a), and the other is deployed vertically in front of the horizontal set and can rotate responding to the solar azimuth trajectory. Two sets of slats work parametrically together to keep the reflected light onto a specific target on the ceiling. This system has two rotation axes, the Z-axis pivot for the vertical louver and the X-axis pivot for the horizontal louver. Sunlight strikes the vertical louver first which can rotate automatically around the Z-axis by responding to the sun azimuth, in order to reflect the light to a direction perpendicular to the façade. Then the horizontal louver rotates automatically around the X-axis to redirect the received reflected towards a specific target on the ceiling.

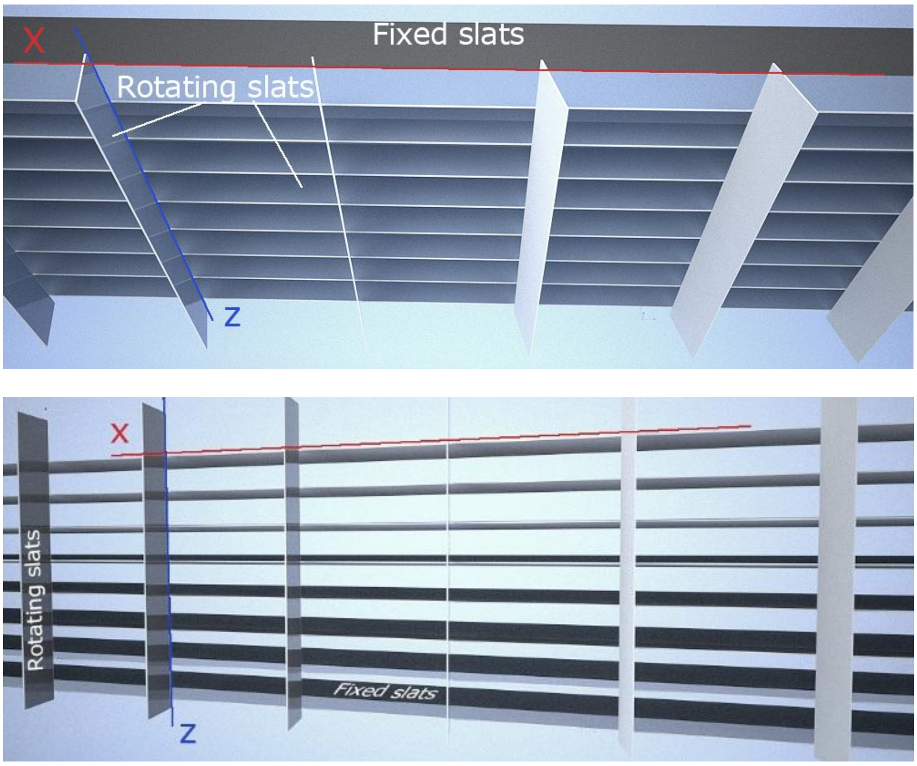


Figure 9: Two-layer parametric louver system

Both vertical and horizontal louvers are rotated parametrically and simultaneously by using a predefined formula created in Grasshopper, with the consideration that each louver has its proper rotation angle. The vertical louver is arrayed along the façade with a distance 60 cm between slats and the width of each slat is 20 cm. The width of the horizontal louver slats was determined as 20 cm, while their length is related to the room length and the number of slats was set to 10. A protrusion as a set of fixed slats was attached to the horizontal louver – likewise the one-axis louver system – to shade the excessive scattered light passing between the slats (Eltaweel and Su, 2017d) and protect from potential glare and excessive brightness.

3.2 Window glass

The above two versions of automated parametric louver system can achieve more uniform daylight illuminance distribution on the ceiling but need to be supplemented with transmittance switchable windows to achieve a steadier level of daylight in a room. For visual comfort, solar intensity inside the office room should be within the acceptable range for occupants. Regarding the CIE and ER standard (Dubois, 2001; Staff, 2004), the provided light at the disk level 0.75m from the floor should be between 300~500 lux to meet the human visual comfort; however, other studies claim that it can be between 200~550 lux, meanwhile, some experiments proved that 100~1000 lux is acceptable for human, depending on the types of tasks (Dubois, 2001). Our study will use the range of 300~500 lux as a criterion to set the simulation control and evaluate the provided daylight by the proposed system. In order to control the level of daylight inside a room, two types of glass can be employed along with the proposed automated parametric louver system, that is, a translucent electrochromic window (Li et al., 2015) is assigned at the lower part of the façade, while a transparent thermochromic window (Kim and Todorovic, 2013) is assigned at the upper part of the facade.

3.2.1 Electrochromic glass

The electrochromic window at the lower part of façade works as a dimmable glazing system which is capable of transforming from transparent “clear” to translucent “haze” phase by using electrical pulse control (Lee et al., 2006). The translucent phase used as a source of diffuse light to lit the closest area near the window within 200 cm away from the window, and controlled parametrically in Grasshopper within the whole system aiming to keep the amount of the penetrated light over the desk level between 300~500 lux which adapted by using test points at the desk level. The translucent phase tends to disperse the incident light from the sun, which means more equally distributed light and lower glare rather than direct light, accordingly, better daylighting performance for human visual comfort (Baker and Steemers, 2014).

The adaptation process will be specified by using a specific component in the Honeybee plugin called “Honeybee Translucent Material” (Mead, 2017). This component has several parameters such as ‘reflectivity, specularity, diffuse transmission and roughness’. Diffuse transmission is responsible for the translucency function. Diffuse transmission can be set between 0.01 (almost opaque) and 1 (transparent), while any value in-between specifies the transmittance amount. A formula was created in Grasshopper to control daylight penetration (solar intensity). The formula represents a relation between diffuse transmission and solar radiation intensity. The diffuse transmission of translucent material was determined at 0.01 ~ 0.07 (as a translucency level), in order to control the daylight illuminance within 300 ~ 500 lux at the adjacent area to the window. For instance, if solar radiation is 790 W/m^2; the diffuse transmission will be automatically set to 0.01, so the daylight penetration will be reduced from 20,000 lux to 400 lux (Eltaweel and Su, 2017d).

3.2.2 Thermochromic glass

The thermochromic window is installed at the upper part of the façade and controlled automatically based on temperature level (Konstantoglou and Tsangrassoulis, 2016; Parkin et al., 2008) while it can change its transmission level according to solar intensity. Accordingly, the higher solar heat it absorbs, the less light level is passing through it and thus keeps the reflected light from the louver at a constant intensity (Taveres-Cachat et al., 2017). For more efficient daylighting system, this window will do the function of keeping the penetrated light intensity in balance.

Smart windows, specially, thermochromic windows can be specified with U-value, g-value (which also called Solar Factor “SF” or Solar Heat Gain Coefficient “SHGC”), solar transmittance (T_{sol}) and visible solar transmittance (T_{vis}) (Jelle, 2013). For such window, the highest and lowest values for the clearest and darkest state may vary according to the type of thermochromic window. A g-value of 1.0 represents full transmittance of solar radiation, while, 0.0 represents a window with no solar transmittance. The utility of thermochromic window in our study is that it can significantly reduce the infrared penetration of solar radiation (heat gain).

Note that all these factors are translated in Grasshopper as parameters in "Honeybee component", and this study focuses on daylight impact and visual comfort. Sensor points were used over both windows by using "TestPoints" component in Honeybee to measure the amount of solar radiation over each window, which then influences parametrically on the parameters of the window to determine the amount of their penetration.

4 Comparison of three parametric louver systems

A comparison is given here between the bi-axis, two-layer and one-axis parametric louver systems. The analysis was conducted for a deep-plan office room with8 m depth and 18 m length, aiming to cover the whole office with more uniform and steadier daylight within illuminance range 300~500 lux.

The percentage daylight coverage is defined as the ratio of the area with the daylight illuminance of 300~500 lux relative to the total floor area, and it was measured using test points of 50 cm grid size at the desk level at 0.75m above the floor (Staff, 2004). The study ignored the edge area within 50cm from the walls around the room, while this area is usually not exploited by the occupants based on usual office designs, in addition, the illuminance level at the two side walls is usually between 100~300 lux due to penumbra effect (Salazar Trujillo, 2014). Generally, lighting in the overall area should be not less than 100 lux at any time during the day (Dubois, 2001). By ignoring the 50cm area around the inner walls, the opportunity of achieving 300-500 lux is better, and the percentage of daylight coverage can reach more than 95% during the daytime. The illuminance values at those test points were used to calculate the percentage daylight coverage for the acceptable range 300~500 lux. Usually, 70% coverage for the daylight range of 300~500 lux is acceptable for typical daylighting systems (Eltaweel and Su, 2017c; Konstantoglou and Tsangrassoulis, 2016; Meresi, 2016). Over 90% coverage is the targeted range where a significant amount of electrical energy can be saved. The rest 10% of the floor area most likely close to the edge does usually have more than 500 lux or less than 300 lux by around 50 lux, which can be accepted or even ignored to be compensated with electrical lighting.

The location, Cairo International Airport represents a hot arid territory, where the sunny weather is dominant throughout a whole year, and solar altitude reaches 83°

at the zenith time in summer. The ray-tracing study can be seen in Figure 10 showing the ray-tracing at 9 am, 12 pm and 3 pm on the 21st of September as a standard case. In Figure 11, the points in the middle of the room represent the targets, and it is evident that the reflected light by the one-axis parametric louver system is moving along the room in different directions, while the bi-axis and two-layer parametric louver systems are respecting the targets during the daytime, i.e., the daylight coverage should be more constant during the working hours comparing to the one-axis louver system.

The target points are employed to equally distribute the daylight over the ceiling to compensate the illumination lack at any specific area. For instance, in June, the sun angle at zenith time is almost perpendicular, i.e. a south oriented room is almost dim during the daytime, especially the deep area of the room. Therefore, the targets should be deployed towards the deep area to compensate the lack of daylight.

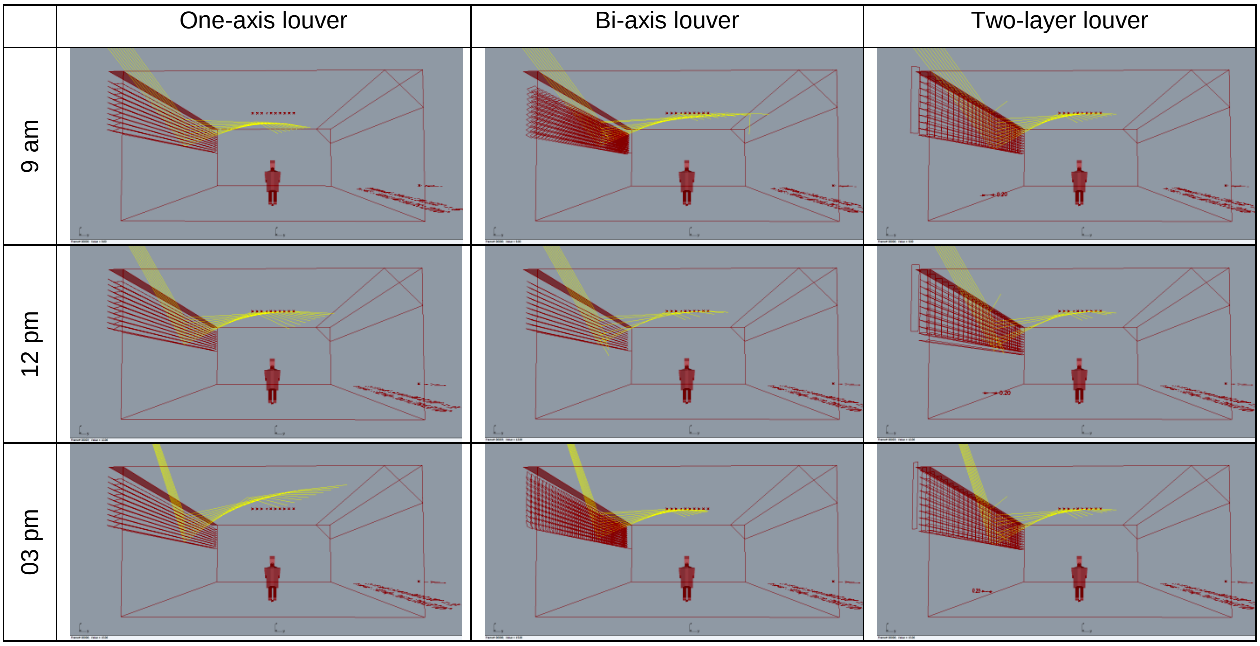


Figure 10: Perspective view showing the ray-tracing directions for the One-axis, Bi-axis and Two-layer parametric louver systems, respectively, at 9 am, 12 pm and 3 pm on September 21st.

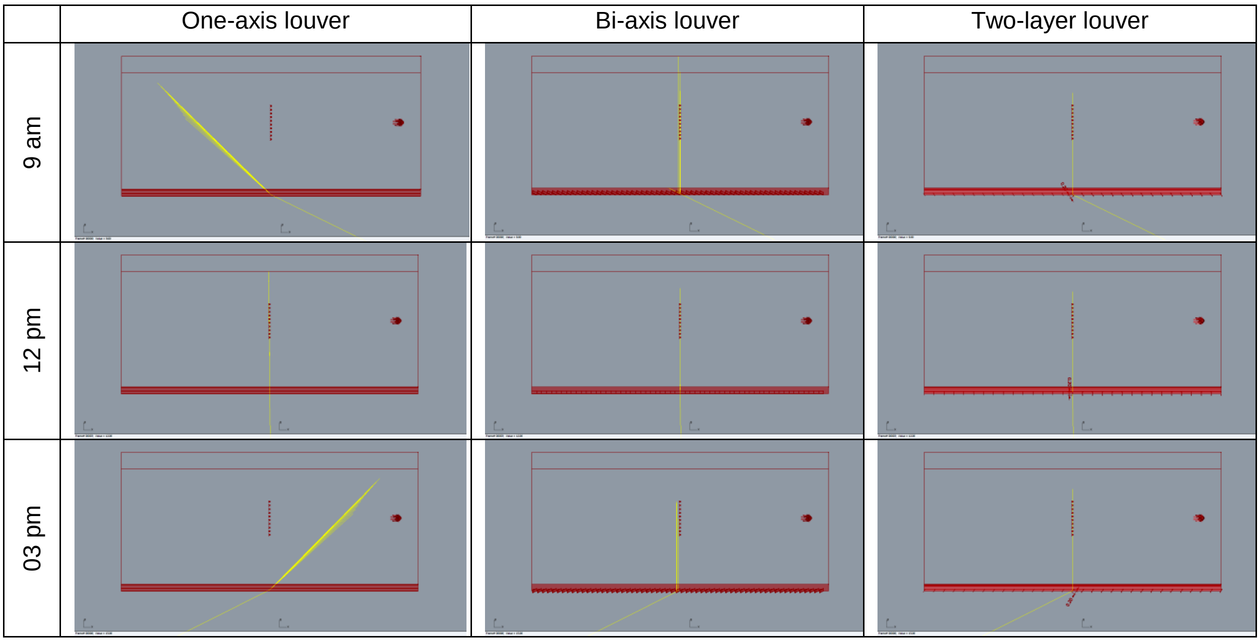


Figure 11: Top view for the office room showing the ray-tracing directions for the One-axis, Bi-axis and Two-layer parametric louver systems, respectively, at 9 am, 12 pm and 3 pm on September 21st.

A comparison was made for four different dates throughout the year, to cover all the possibilities of sun positions. The selected dates are 21st of March, 21st of June, 21st of September and 21st of December as they are representing different seasons and different altitudes, see Figure 12, Figure 13, Figure 14 and Figure 15. Note that the simulation has been made under the sky type "Climate-based daylighting modelling" (CBDM) via using EPW weather file (Brembilla and Mardaljevic, 2019). In Figure 16, Figure 17, Figure 18 and Figure 19 it can be observed that the coverage is almost the same between the three louver systems, however, slightly better performance revealed in the Bi-axis system especially at 4 pm in March, June and September due to the benefits of the fixed targets. Meanwhile, we can observe a typical attitude between three louver systems, the dark blue triangular area on the left side near to the wall in the late evening hours and even on the right area in the morning hours. This means that these areas are not receiving enough light. Although the new proposed systems; Bi-axis and Two-layer systems are entirely following the sun movement, however, they are almost performing similar the One-axis louver system. Therefore, this issue has been significantly considered in the following section.

The parametric louver can deliver a fairly-uniform distribution of reflected light on the most part of a ceiling, while the intensity of penetrated light needs to be controlled with the changeable transmittance of the upper thermochromic window of a façade. In simulation, the transmittance of the upper thermochromic window was varied between 0.35 – 0.95 according to the solar irradiance on the front surface of window. In a similar way, the transmittance of the lower electrochromic window is adjusted to control the illuminance level in the area near the window. The transmittance of two windows is controlled parametrically using an algorithmic formula created in Grasshopper, as summarized in a schematic diagram in **Figure 20**. The diffuse horizontal irradiance (DHI) and the direct normal irradiance (DNI) from the EPW data file were used to calculate the preliminary transmittance required, which is then adjusted in order to maximise the percentage daylight coverage for the range of 300~500 lux. As an example, Table 2 demonstrates the window control values calculated by Grasshopper.

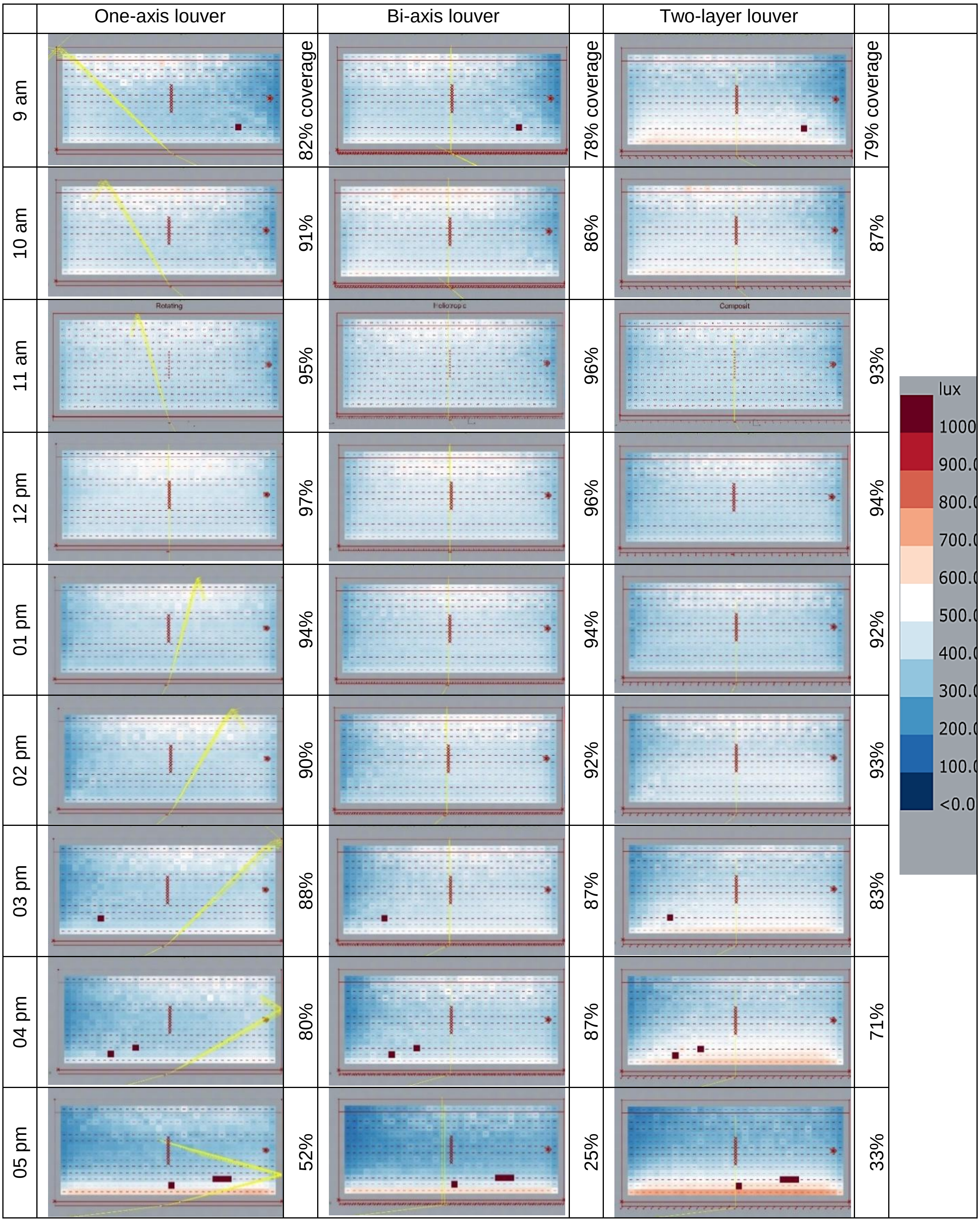


Figure 12: Percentage daylight coverage in the range of 300-500 lux for the One-axis, Biaxial and Two-axis parametric louver systems, respectively, on the 22nd of March.

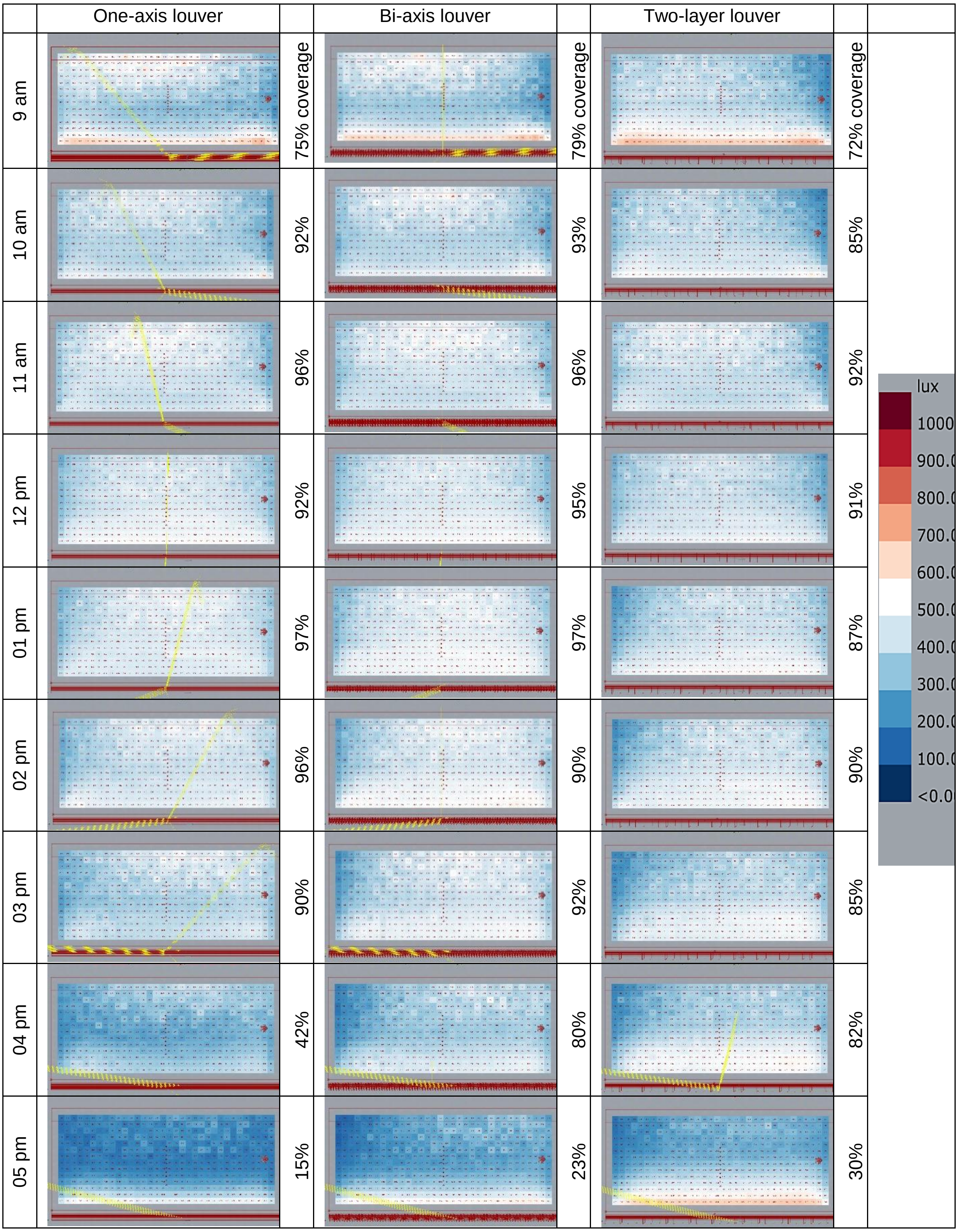


Figure 13: Percentage daylight coverage in the range of 300-500 lux for the One-axis, Biaxial and Two-axis parametric louver systems, respectively, on the 21st of June.

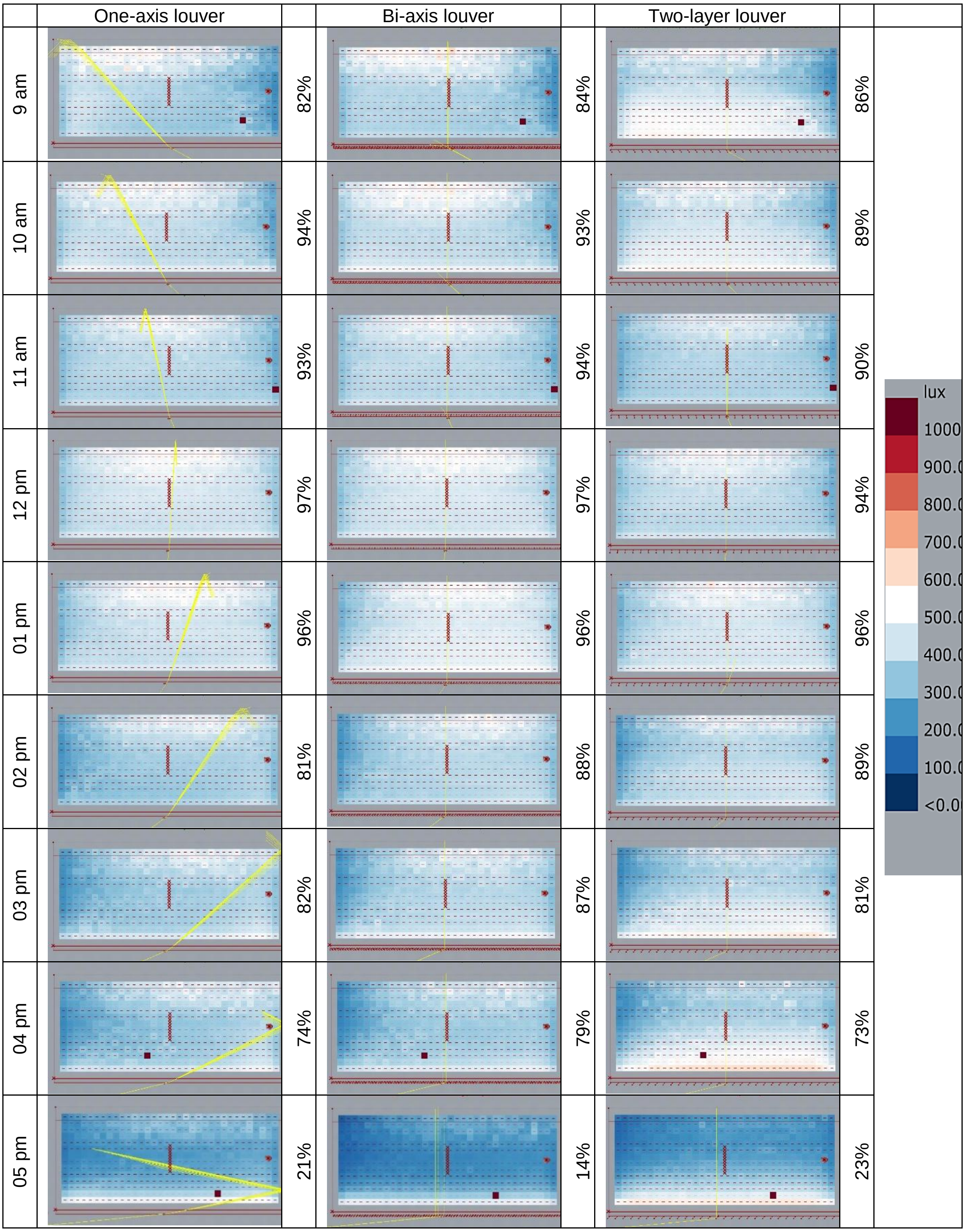


Figure 14: Percentage daylight coverage in the range of 300-500 lux for the One-axis, Biaxial and Two-axis automated louver systems, respectively, on the 21st of September.

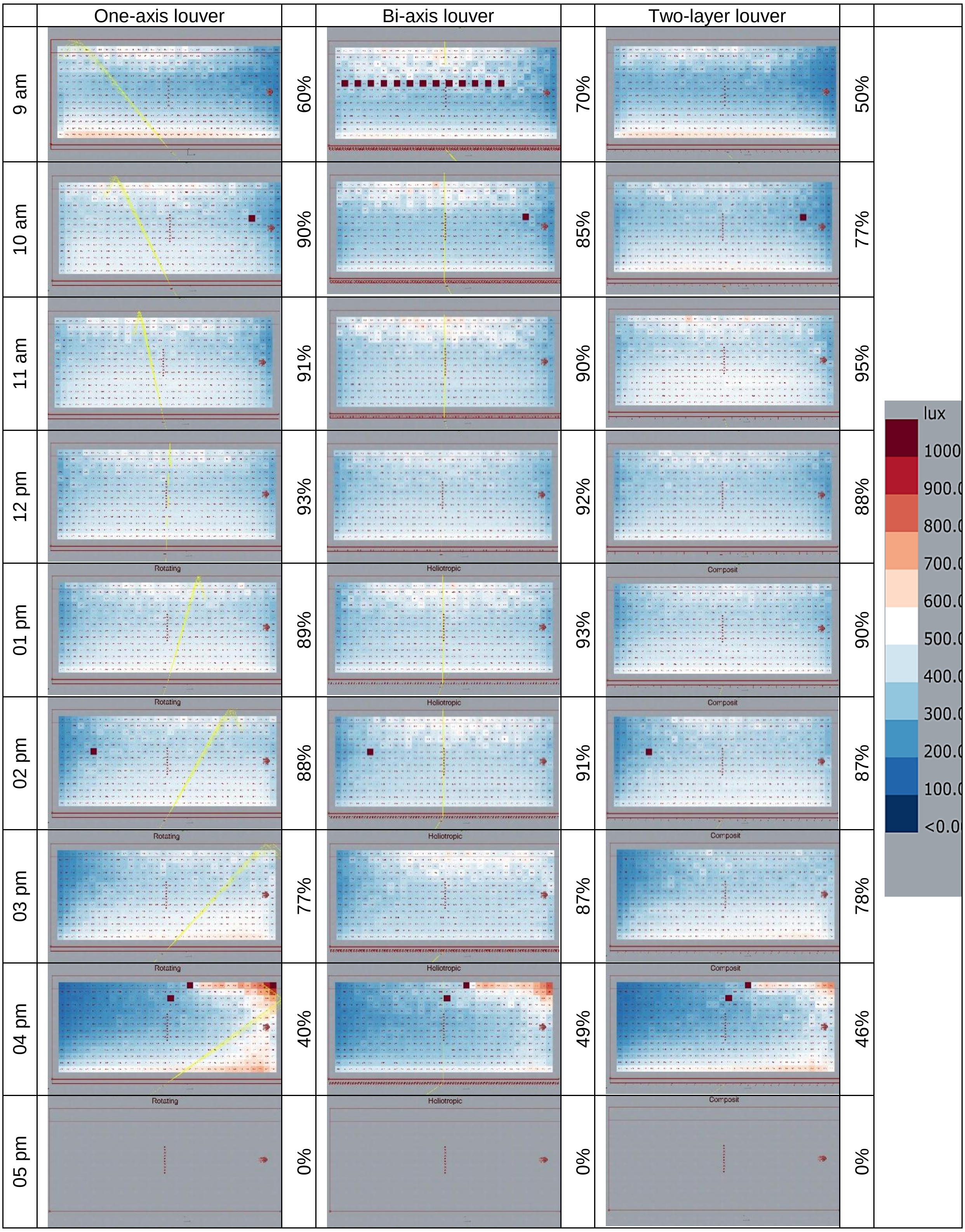
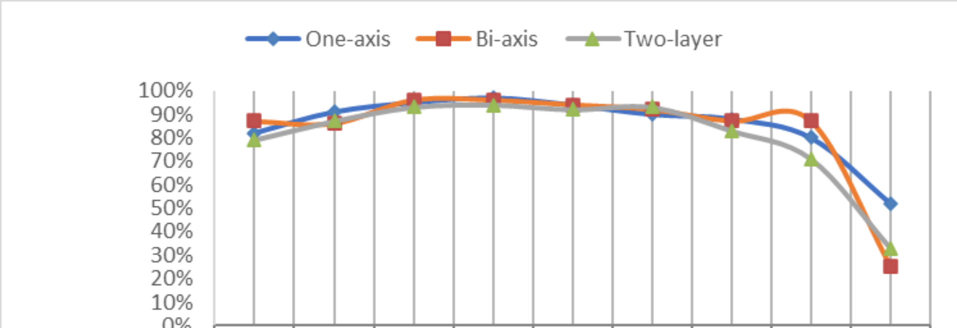
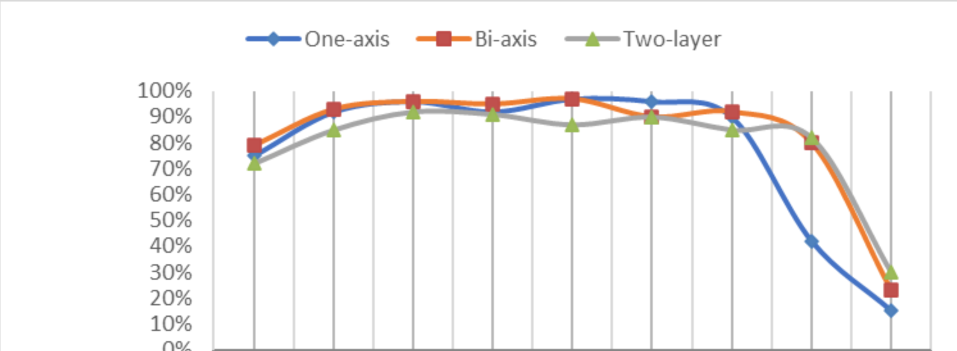


Figure 15: Percentage daylight coverage in the range of 300-500 lux for the One-axis, Bi-axial and Two-axis parametric louver systems, respectively, on the 21st of December.



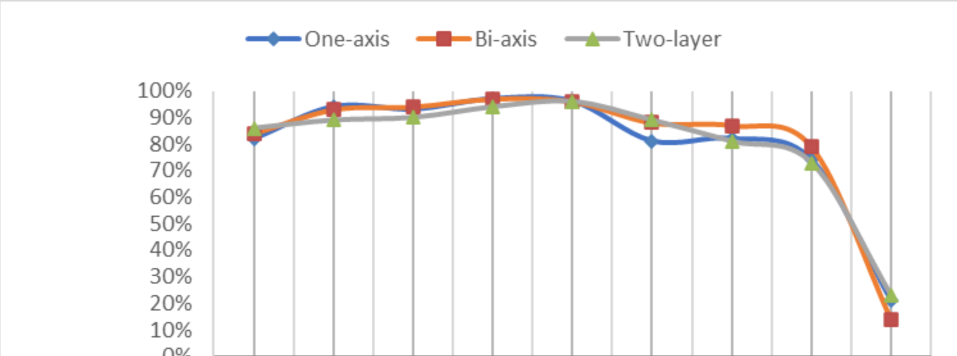
	9:00 AM	10:00 AM	11:00 AM	12:00 PM	1:00 PM	2:00 PM	3:00 PM	4:00 PM	5:00 PM
One-axis	82%	91%	95%	97%	94%	90%	88%	80%	52%
Bi-axis	87%	86%	96%	96%	94%	92%	87%	87%	25%
Two-layer	79%	87%	93%	94%	92%	93%	83%	71%	33%

Figure 16: Percentage daylight coverage in the range of 300-500 lux for three parametric louver systems during working hours on the 21st of March.



	9:00 AM	10:00 AM	11:00 AM	12:00 PM	1:00 PM	2:00 PM	3:00 PM	4:00 PM	5:00 PM
One-axis	75%	92%	96%	92%	97%	96%	90%	42%	15%
Bi-axis	79%	93%	96%	95%	97%	90%	92%	80%	23%
Two-layer	72%	85%	92%	91%	87%	90%	85%	82%	30%

Figure 17: Percentage daylight coverage in the range of 300-500 lux for three parametric louver systems during working hours on the 21st of June.



	9:00 AM	10:00 AM	11:00 AM	12:00 PM	1:00 PM	2:00 PM	3:00 PM	4:00 PM	5:00 PM
One-axis	82%	94%	93%	97%	96%	81%	82%	74%	21%
Bi-axis	84%	93%	94%	97%	96%	88%	87%	79%	14%
Two-layer	86%	89%	90%	94%	96%	89%	81%	73%	23%

Figure 18: Percentage daylight coverage in the range of 300-500 lux for three parametric louver systems during working hours on the 21st of September.

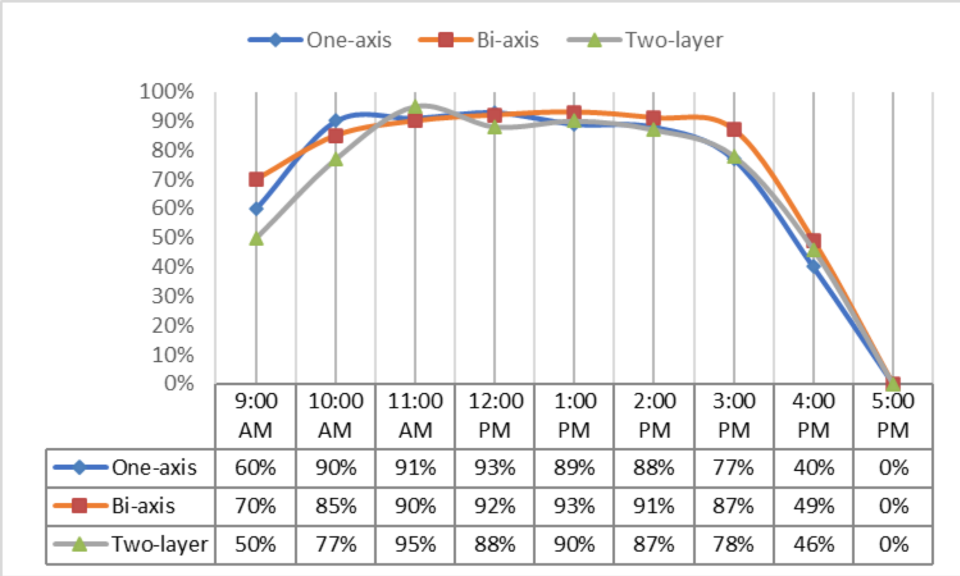


Figure 19: Percentage of daylight coverage in the range of 300-500 lux for three parametric louver systems during working hours on the 21st of December.

Table 2: Solar irradiance values on the 21st of September from 9 am to 5 pm and calculated glass transmittance. Note: the arrows represent a direct influence.

Day time	(GHI) Global horizontal irradiance W/m²	(DNI) Direct normal irradiance W/m²	(DHI) Diffuse horizontal irradiance W/m²	Solar irradiation on the south window W/m²	Upper window – Thermochromic glass transmittance	Lower window – Electrochromic glass transmittance	Percentage of daylight coverage
9:00	297	128	214	207	0.6	0.02	84%
10:00	588	497	200	407	0.65	0.02	92%
11:00	848	883	94	582	0.85	0.01	93%
12:00	941	969	96	644	0.85	0.01	97%
13:00	967	1051	94	659	0.85	0.01	96%
14:00	823	915	152	567	0.65	0.01	81%
15:00	639	788	177	434	0.7	0.02	82%
16:00	441	691	164	292	0.9	0.03	74%
17:00	234	568	127	144	0.95	0.03	21%

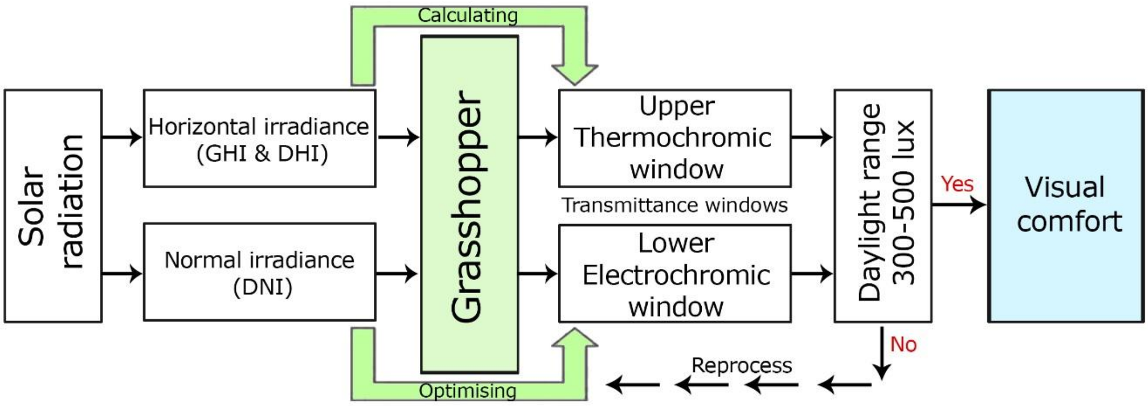


Figure 20: A diagram showing the process in Grasshopper to control the window transmission.

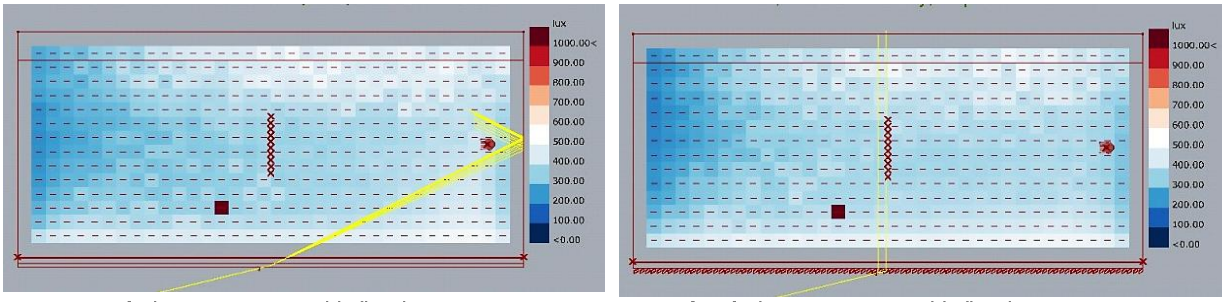
5 Discussion on further improvement with amendable target points

The results in Figure 186 to 19 show insufficient daylight illumination from 4 pm due to larger solar azimuth, even for the bi-axis and two-layer louver systems which are able reflect sunlight at larger solar azimuth to the fixed targets. However, we can solve this issue via changing the positions of those target points on the ceiling to the less illuminated side area when solar azimuth is larger, thanks to the parametric design that allows controlling different parameters including target points simultaneously. For instance, at 4 pm if we move the target points 3 meters to the west on the ceiling, the reflected light will be directed onto the dark blue area to compensate the weakness of daylight at this time as shown in **Figure 21**. Significantly, we can observe that the blue area near to the wall almost disappears after moving the targets to the left side, which improved the daylight in this area. More than 10% increment is obtained (from 79% to 93%) comparing to the original target positions, so this shift of target position could be considered as a promising method for better daylight coverage in early morning or late afternoon.

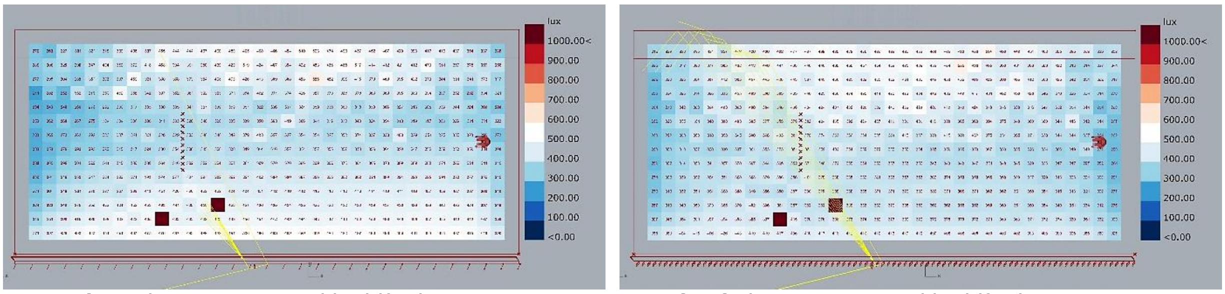
Shifting of the target points were determined parametrically when the less illuminated area appears near the side wall at larger solar azimuth. For instance, at 2 pm when the sensor points records a value less than 300 lux at 1 meter to the left wall (equivalent to 2 columns of test points), all target points will be parametrically shifted by 1 meter towards the left side, and so forth.

After applying this shift during the day, we can observe substantial improving at the early and late hours, as shown in **Figure 22**. It can be seen that the Two-layer louver system is giving better performance ranging between 79 – 96%, which is above the accepted range 70%. Meanwhile, the Bi-axis louver system is ranging between 91 – 98%, which is above the targeted amount 90%; accordingly, daylight performance is significantly improved, which means that steadier illumination of daylight can be provided during the daytime and no need for electrical lighting.

As a location in hot arid territory, New Cairo was chosen due to its dominant clear sky condition. Although this advanced parametric louver system should be preferably applied in territories with clear sky conditions, the system can be efficiently work even with more often intermediate and cloudy sky conditions like UK weather (Eltaweel and Su, 2017b).

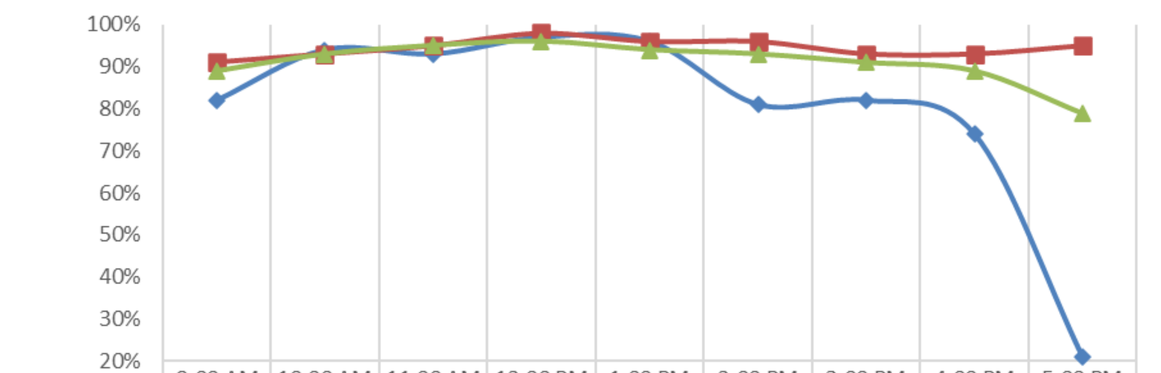


One-axis louver system with fixed targets: **74%** | **Bi-axis** louver system with fixed targets: **79%**



Two-layer louver system with shifted targets: **89%** | **Bi-axis** louver system with shifted targets: **93%**

Figure 21: Percentage daylight coverage in the range of 300-500 lux before and after applying the shifted targets at 4 pm on the 21st of September



	9:00 AM	10:00 AM	11:00 AM	12:00 PM	1:00 PM	2:00 PM	3:00 PM	4:00 PM	5:00 PM
One-axis	82%	94%	93%	97%	96%	81%	82%	74%	21%
Biaxis	91%	93%	95%	98%	96%	96%	93%	93%	95%
Two-axis	89%	93%	95%	96%	94%	93%	91%	89%	79%

Figure 22: Percentage daylight coverage in the range of 300-500 lux for three parametric louver systems after applying the shifted targets, on September 21st.

6 Conclusion

A comparison analysis was conducted for a south-oriented office room to evaluate the daylight availability during the daytime by using three daylighting louver systems with different methods based on collect and redirect the sunlight to the ceiling inside the building envelope. The systems were defined as; One-axis parametric louver, Bi-axis parametric louver and Two-layer parametric louver, where, the two latter systems can entirely track the sun movement. The whole daylighting systems were controlled parametrically using a predefined algorithmic formula created in Grasshopper. Ladybug and Honeybee were used as plugin to run Radiance and DAYSIM for daylighting analysis. The study aimed to evaluate the performance of each system by using an improved redirecting method with the aid of smart windows. Electrochromic and thermochromic windows were used as switchable smart windows to control the amount of daylight penetration into the room in order to obtain an acceptable illuminance range 300~500 lux for the occupants' visual comfort according to CIE standards.

With fixed target points on a ceiling, three parametric louver systems can all achieve more than 70% of daylight coverage for most of working hours between 9:00am~5:00pm throughout the year, but the advanced bi-axis and two-layer louver systems could provide steadier daylight illumination for longer duration. Furthermore, with shifted target points, the advanced bi-axis and two-layer louver systems show a great advantage by providing more than 90% and 80% of daylight coverage respectively for the whole working hours between 9:00am~5:00pm. Accordingly, as long as steadier and more uniform daylight is provided and could meet the occupants' visual comfort 300~500 lux at the desk level, electrical light can be entirely saved during the working hours.

In comparison, the Two-layer parametric louver system can be considered more practical technology compared to the Bi-axis louver system, because the former is much simpler in operation while the latter has a relatively complicated rotational structure. A future study will investigate the feasibility of such system by using much smaller slats in order to be applied within a double glazing, using different shapes of slats (concave & convex) for more graceful material and using lighter weight of slats for more feasibility.

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References

Aburas, M., Soebarto, V., Williamson, T., Liang, R., Ebendorff-Heidepriem, H., Wu, Y., 2019. Thermochromic smart window technologies for building application: A review. Applied Energy 255, 113522. DOI: https://doi.org/10.1016/j.apenergy.2019.113522.

Al-Obaidi, K.M., Munaaim, M.A.C., Ismail, M.A., Abdul Rahman, A.M., 2017. Designing an integrated daylighting system for deep-plan spaces in Malaysian low-rise buildings. Solar Energy 149, 85-101. DOI: https://doi.org/10.1016/j.solener.2017.04.001.

Associates, R.M., 2017. Rhinoceros. https://www.rhino3d.com/.

Baetens, R., Jelle, B.P., Gustavsen, A., 2010. Properties, requirements and possibilities of smart windows for dynamic daylight and solar energy control in buildings: A state-of-the-art review. Solar energy materials and solar cells 94(2), 87-105.

Baker, N., Steemers, K., 2014. Daylight design of buildings: a handbook for architects and engineers. Routledge.

Boubekri, M., 2008. Daylighting, Architecture and Health. Taylor & Francis.

Brembilla, E., Mardaljevic, J., 2019. Climate-Based Daylight Modelling for compliance verification: Benchmarking multiple state-of-the-art methods. Building and Environment 158, 151-164. DOI: https://doi.org/10.1016/j.buildenv.2019.04.051.

Chi, F.a., Wang, R., Li, G., Xu, L., Wang, Y., Peng, C., 2020. Integration of sun-tracking shading panels into window system towards maximum energy saving and non-glare daylighting. Applied Energy 260, 114304. DOI: https://doi.org/10.1016/j.apenergy.2019.114304.

Davidson, S., 2020. Grasshopper. http://www.grasshopper3d.com/. 2019).

Dubois, M.-C., 2001. Impact of shading devices on daylight quality in offices. Simulations with Radiance.

Dussault, J.-M., Gosselin, L., 2017. Office buildings with electrochromic windows: A sensitivity analysis of design parameters on energy performance, and thermal and visual comfort. Energy and Buildings 153, 50-62. DOI: https://doi.org/10.1016/j.enbuild.2017.07.046.

El Daly, H.M.T., 2014. Automated fenestration allocation as complying with LEED rating system. Alexandria Engineering Journal 53(4), 883-890. DOI: http://dx.doi.org/10.1016/j.aej.2014.09.011.

Eltaweel, A., Mandour, M.A., Lv, Q., Su, Y., 2020. Daylight Distribution Improvement Using Automated Prismatic Louvre. Journal of Daylighting 7(1), 84-92.

Eltaweel, A., Su, Y., 2017a. Controlling venetian blinds based on parametric design; via implementing Grasshopper's plugins: A case study of an office building in Cairo. Energy and Buildings 139, 31-43. DOI: http://dx.doi.org/10.1016/j.enbuild.2016.12.075.

Eltaweel, A., Su, Y., 2017b. Evaluation of Suitability of a Parametrically Controlled Louvers for Various Orientations throughout a Year Comparing to an Existing Case. Buildings 7(4), 109.

Eltaweel, A., Su, Y., 2017c. Parametric design and daylighting: A literature review. Renewable and Sustainable Energy Reviews 73, 1086-1103. DOI: http://dx.doi.org/10.1016/j.rser.2017.02.011.

Eltaweel, A., Su, Y., 2017d. Using integrated parametric control to achieve better daylighting uniformity in an office room: A multi-Step comparison study. Energy and Buildings 152, 137-148. DOI: https://doi.org/10.1016/j.enbuild.2017.07.033.

Erlendsson, Ö., 2014. Daylight Optimization-A Parametric Study of Atrium Design: Early Stage Design Guidelines of Atria for Optimization of Daylight Autonomy.

Fasi, M.A., Budaiwi, I.M., 2015. Energy performance of windows in office buildings considering daylight integration and visual comfort in hot climates. Energy and Buildings 108, 307-316. DOI: http://dx.doi.org/10.1016/j.enbuild.2015.09.024.

Fernandes, L.L., Lee, E.S., Ward, G., 2013. Lighting energy savings potential of split-pane electrochromic windows controlled for daylighting with visual comfort. Energy and Buildings 61, 8-20. DOI: https://doi.org/10.1016/j.enbuild.2012.10.057.

Granqvist, C.G., 2016. Recent progress in thermochromics and electrochromics: A brief survey. Thin Solid Films 614, 90-96. DOI: https://doi.org/10.1016/j.tsf.2016.02.029.

Granqvist, C.G., Arvizu, M.A., Pehlivan, İ.B., Qu, H.-Y., Wen, R.-T., Niklasson, G.A., 2018. Electrochromic materials and devices for energy efficiency and human comfort in buildings: A critical review. Electrochimica Acta 259, 1170-1182.

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. DOI: https://doi.org/10.1016/j.enbuild.2010.05.024.

Hashemi, A., 2014. Daylighting and solar shading performances of an innovative automated reflective louvre system. Energy and Buildings 82, 607-620. DOI: http://dx.doi.org/10.1016/j.enbuild.2014.07.086.

Henriques, G.C., Duarte, J.P., Leal, V., 2012. Strategies to control daylight in a responsive skylight system. Automation in Construction 28, 91-105. DOI: http://dx.doi.org/10.1016/j.autcon.2012.06.002.

Hernández, F.F., Cejudo López, J.M., Peña Suárez, J.M., González Muriano, M.C., Rueda, S.C., 2017. Effects of louvers shading devices on visual comfort and energy demand of an office building. A case of study. Energy Procedia 140, 207-216. DOI: https://doi.org/10.1016/j.egypro.2017.11.136.

Jelle, B.P., 2013. Solar radiation glazing factors for window panes, glass structures and electrochromic windows in buildings—Measurement and calculation. Solar Energy Materials and Solar Cells 116, 291-323. DOI: https://doi.org/10.1016/j.solmat.2013.04.032.

Jelle, B.P., Hynd, A., Gustavsen, A., Arasteh, D., Goudey, H., Hart, R., 2012. Fenestration of today and tomorrow: A state-of-the-art review and future research opportunities. Solar Energy Materials and Solar Cells 96, 1-28.

Kim, J.T., Todorovic, M.S., 2013. Tuning control of buildings glazing's transmittance dependence on the solar radiation wavelength to optimize daylighting and building's energy efficiency. Energy and Buildings 63, 108-118. DOI: http://dx.doi.org/10.1016/j.enbuild.2013.03.036.

Konis, K., Lee, E.S., 2015. Measured daylighting potential of a static optical louver system under real sun and sky conditions. Building and Environment 92, 347-359. DOI: http://dx.doi.org/10.1016/j.buildenv.2015.04.024.

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

Lee, E.S., DiBartolomeo, D.L., Selkowitz, S.E., 1998. Thermal and daylighting performance of an automated venetian blind and lighting system in a full-scale private office. Energy and Buildings 29(1), 47-63. DOI: https://doi.org/10.1016/S0378-7788(98)00035-8.

Lee, E.S., Selkowitz, S.E., Clear, R.D., DiBartolomeo, D.L., Klems, J.H., Fernandes, L.L., Ward, G.J., Inkarojrit, V., Yazdanian, M., 2006. Advancement of electrochromic windows. Lawrence Berkeley National Laboratory.

Li, D.H.W., Lam, J.C., Wong, S.L., 2005. Daylighting and its effects on peak load determination. Energy 30(10), 1817-1831. DOI: https://doi.org/10.1016/j.energy.2004.09.009.

Li, G., Xuan, Q., Akram, M.W., Golizadeh Akhlaghi, Y., Liu, H., Shittu, S., 2020. Building integrated solar concentrating systems: A review. Applied Energy 260, 114288. DOI: https://doi.org/10.1016/j.apenergy.2019.114288.

Li, G., Xuan, Q., Zhao, X., Pei, G., Ji, J., Su, Y., 2018. A novel concentrating photovoltaic/daylighting control system: Optical simulation and preliminary experimental analysis. Applied Energy 228, 1362-1372. DOI: https://doi.org/10.1016/j.apenergy.2018.07.024.

Li, Z., Ju, J., Xu, W., 2015. Daylighting Control Performance and Subject Responses to Electrochromic Windows in a Meeting Room. Procedia Engineering 121, 27-32.

Littlefair, P., 1996. Designing with innovative daylighting. Building Research Establishment Watford.

Littlefair, P.J., Aizlewood, M.E., Birtles, A.B., 1994. The performance of innovative daylighting systems. Renewable Energy 5(5), 920-934. DOI: https://doi.org/10.1016/0960-1481(94)90113-9.

Mäkitalo, J., 2013. Simulating control strategies of electrochromic windows: Impacts on indoor climate and energy use in an office building.

Mashaly, I.A., Nassar, K., El-Henawy, S.I., Mohamed, M.W.N., Galal, O., Darwish, A., Hassan, O.N., Safwat, A.M.E., 2017. A prismatic daylight redirecting fenestration system for southern skies. Renewable Energy 109, 202-212. DOI: https://doi.org/10.1016/j.renene.2017.02.048.

Mayhoub, M.S., 2014. Innovative daylighting systems' challenges: A critical study. Energy and Buildings 80, 394-405. DOI: http://dx.doi.org/10.1016/j.enbuild.2014.04.019.

Mayhoub, M.S., 2019. Fifty years of building core sunlighting systems – Eight lessons learned. Solar Energy 184, 440-453. DOI: https://doi.org/10.1016/j.solener.2019.03.097.

McNeel, 2020. food4Rhino. http://www.food4rhino.com/. 2019).

Mead, D., 2017. Trans Materials Modeling and Specifying a Next Generation. https://radiance-online.org//community/workshops/2010-freiburg/PDF/DavidMead.pdf.

Meresi, A., 2016. Evaluating daylight performance of light shelves combined with external blinds in south-facing classrooms in Athens, Greece. Energy and Buildings 116, 190-205. DOI: http://dx.doi.org/10.1016/j.enbuild.2016.01.009.

Nielsen, M.V., Svendsen, S., Jensen, L.B., 2011. Quantifying the potential of automated dynamic solar shading in office buildings through integrated simulations of energy and daylight. Solar Energy 85(5), 757-768. DOI: http://dx.doi.org/10.1016/j.solener.2011.01.010.

Orouji, P., Vakili, A., Behrouz, M.K., Jafari, H.H., Eslami, M.R., Vahidnia, M., Moghaddam Sadegh, R., Rezaie, M., 2019. Methodology of standardizing the energy labeling and rating of window fenestration in IRAN. Sustainable Energy Technologies and Assessments 33, 24-33. DOI: https://doi.org/10.1016/j.seta.2019.02.009.

Park, D., Kim, P., Alvarenga, J., Jin, K., Aizenberg, J., Bechthold, M., 2014. Dynamic daylight control system implementing thin cast arrays of polydimethylsiloxane-based millimeter-scale transparent louvers. Building and Environment 82, 87-96. DOI: https://doi.org/10.1016/j.buildenv.2014.07.016.

Parkin, I.P., Binions, R., Piccirillo, C., Blackman, C.S., Manning, T.D., 2008. Thermochromic coatings for intelligent architectural glazing, Journal of Nano research. Trans Tech Publ, pp. 1-20.

Piccolo, A., Simone, F., 2015. Performance requirements for electrochromic smart window. Journal of Building Engineering 3, 94-103. DOI: https://doi.org/10.1016/j.jobe.2015.07.002.

Rahimzadeh, S.D., 2015. Use of parametric modelling and climate-based metrics for the efficient design of daylight strategies in buildings with complex geometries. Queensland University of Technology.

Ramzy, N., Fayed, H., 2011. Kinetic systems in architecture: New approach for environmental control systems and context-sensitive buildings. Sustainable Cities and Society 1(3), 170-177. DOI: https://doi.org/10.1016/j.scs.2011.07.004.

Salazar Trujillo, J.H., 2014. Calculation of the shadow-penumbra relation and its application on efficient architectural design. Solar Energy 110, 139-150. DOI: http://dx.doi.org/10.1016/j.solener.2014.08.043.

Serra, R., 1998. Chapter 6—Daylighting. Renewable and Sustainable Energy Reviews 2(1), 115-155. DOI: https://doi.org/10.1016/S1364-0321(98)00014-8.

Staff, Z., 2004. The lighting handbook. Austria: Zumtobel.

Suyoto, W., Indraprastha, A., Purbo, H.W., 2015. Parametric Approach as a Tool for Decision-making in Planning and Design Process. Case study: Office Tower in Kebayoran Lama. Procedia - Social and Behavioral Sciences 184, 328-337. DOI: http://dx.doi.org/10.1016/j.sbspro.2015.05.098.

Tällberg, R., Jelle, B.P., Loonen, R., Gao, T., Hamdy, M., 2019. Comparison of the energy saving potential of adaptive and controllable smart windows: A state-of-the-art review and simulation studies of thermochromic, photochromic and electrochromic technologies. Solar Energy Materials and Solar Cells 200, 109828. DOI: https://doi.org/10.1016/j.solmat.2019.02.041.

Taveres-Cachat, E., Grynning, S., Almas, O., Goia, F., 2017. Advanced transparent facades: market available products and associated challenges in building performance simulation. Energy Procedia 132, 496-501. DOI: https://doi.org/10.1016/j.egypro.2017.09.685.

Tian, C., Chen, T., Chung, T.-m., 2014. Experimental and simulating examination of computer tools, Radlink and DOE2, for daylighting and energy simulation with venetian blinds. Applied Energy 124, 130-139. DOI: https://doi.org/10.1016/j.apenergy.2014.03.002.

Tsangrassoulis, A., 2008. A review of innovative daylighting systems. Advances in Building Energy Research 2(1), 33-56.

Van Den Wymelenberg, K., 2012. Patterns of occupant interaction with window blinds: A literature review. Energy and Buildings 51, 165-176. DOI: http://dx.doi.org/10.1016/j.enbuild.2012.05.008.

Wagdy, A., Fathy, F., 2015. A parametric approach for achieving optimum daylighting performance through solar screens in desert climates. Journal of Building Engineering 3, 155-170.

Xuan, Q., Li, G., Lu, Y., Zhao, B., Zhao, X., Pei, G., 2019. Daylighting characteristics and experimental validation of a novel concentrating photovoltaic/daylighting system. Solar Energy 186, 264-276. DOI: https://doi.org/10.1016/j.solener.2019.05.014.

Xue, P., Mak, C.M., Cheung, H.D., 2014. New static lightshelf system design of clerestory windows for Hong Kong. Building and Environment 72(Supplement C), 368-376. DOI: https://doi.org/10.1016/j.buildenv.2013.11.017.

Ye, H., Meng, X., Xu, B., 2012. Theoretical discussions of perfect window, ideal near infrared solar spectrum regulating window and current thermochromic window. Energy and Buildings 49, 164-172.