Visual Discomfort Analysis as a Tool to Support Façade Shading Design: A Case Study in the Architectural Design Studio

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Abstract

Whilst daylight admittance in educational buildings is of a high importance, the associated visual discomfort issues can negatively impact students' productivity and wellbeing. This paper reports the outcomes of a case study of the architectural studios at Al-Azhar University, Cairo where visual discomfort was reported by 49% of the students, leading to difficulties while performing multiple vertical and horizontal tasks. To address this issue, visual discomfort simulation analyses were conducted for 78 view positions to drive facade shading systems (fixed shading and dynamic electrochromic glazing). To predict visual discomfort for multiple view targets, three indicators of horizontal illuminance, vertical-eye illuminance and DGP were used. A simulation workflow of daylight and glare was developed to shade each dynamic window individually whenever the defined criteria are met. The results showed evident reductions in the occupation time receiving visual discomfort based on the three indicators from 83%, 84%, 37% to 8%, 19%, 3% respectively (south-west) and from 57%, 71%, 13% to 2%,10%, 1% respectively (north-east). The proposed simulation workflow can be used in future practices to improve facade shading performance in protecting against visual discomfort under similar climatic contexts.

Keywords: Daylight; Glare; Shading Systems; Simulation; Visual Discomfort

1 Introduction

The application of daylighting simulations as a design tool to support and evaluate building façades designs has expanded in recent years. Utilizing natural daylighting in buildings can fundamentally reduce energy consumption in addition to several non-energy benefits including productivity improvements and enhanced feelings of well-being for building occupants (IES 2011; Reinhart 2014; Konstantzos and Tzempelikos 2014; Boyce 2014). Admitting daylighting has been also highly encouraged in educational buildings to ensure healthy and comfortable environment for the students (Wu and Ng 2003; Plympton et al. 2000; Shishegar and Boubekri 2016). In case of architectural education particularly, sufficient lighting found of high importance for students to be properly facilitated to work and perform different required tasks (e.g. produce drawings, model making, etc.) (Lubis et al. 2018). Nevertheless, if daylighting designs are poorly conceived, the lighting environment may lead to user visual dissatisfaction due to either insufficient light or excessive direct light and glare occurrence. This in turn can cause syndromes of pain, soreness, headaches and fatigue, leading to visual task difficulty, distraction, and perceptual confusion (Boyce 2014; Day et al. 2019). This has increasingly becoming a concern in educational indoor environments, as visual discomfort from daylighting was evidenced to negatively affect students' productivity and wellbeing (Heschong and Mahone 2003).

Designing buildings' facades to abundantly admit daylight through large windows, especially if it is considered solely as a modifier to save building's lighting energy, may result in visual or thermal discomfort issues. In such cases, glare occurrence and overheating sensation may drive the occupants to draw the inner shadings, giving up the advantage of daylighting, and frequently rely on artificial lighting, leading to precisely an opposite performance (Tregenza and Mardaljevic 2018).

For successful facades' shading design, it is crucial to consider causes of user dissatisfaction that lead him/her to routinely draw the shading/blinds (Wienold 2007). In essence, the users manage to activate their shading/blinds mainly to control unwanted daylight when they experience discomfort, and provide protection against discomfort glare and excessive heat gains (Inoue et al. 1988; Reinhart 2003; Van Den Wymelenberg 2012; Kim et al. 2009; Lindsay and Littlefair 1992; Inkarojrit 2005), although the main motivation remains to avoid glare, more than to prevent overheating (Lindsay and Littlefair 1992). This can be highly dependent on the climatic conditions such as the latitude, the sky conditions (i.e., the highest rate of blinds occlusion was monitored under clear sky conditions where the potential for glare from excessive sunlight and sky brightness is more probable) (Rea 1984), time of the day and time of the year and the orientation (i.e., spaces on the south facade found to have the most likelihood to have blinds down) (Van Den Wymelenberg 2012; Inkarojrit 2005; Nezamdoost and Van Den Wymelenberg 2017).

In fact, admitting abundant daylight in buildings can be easily achieved under clear-sky climates whereas preventing glare and overheating remains the main challenge for the designers to resolve. Despite of the large number of studies in the literature sought to improve daylighting performance in buildings under hot clear sky climates, very few studies actually considered addressing visual discomfort issues from daylighting while designing building's façade (Sabry 2014; Singh et al. 2016; Wagdy 2015), specifically in educational buildings (Ishac and Nadim 2021). Also, due to the limitations in the current glare simulation techniques (Jones 2017), visual discomfort analyses have been examined for a very limited number of view positions which cannot be generalized for large spaces with multiple view positions and directions such as the case of educational spaces. There are still gaps lying in addressing visual discomfort issues associated with daylight, known also to negatively impact students' productivity and wellbeing. Therefore, it is recommended that visual discomfort analysis should be incorporated into shading design to a greater extent than what is common practice nowadays (Karlsen et al. 2015). In the following section, a review for visual discomfort quantitative indicators, particularly that trigger shading control, is presented for their reference to be integrated with shading design.

1.1 Indicators of Visual Discomfort from Daylight

Considerable research has investigated the factors influencing user visual discomfort from daylight. These factors were reviewed in the following paragraphs, particularly for excessive conditions that lead the occupants to close the shadings and give up daylighting presence

Shading occlusion has been correlated to external stimuli that result in occupants discomfort using several light indicators (with various thresholds)(Van Den Wymelenberg 2012). In detail, illuminance data has been found to cause users dissatisfaction leading them to close their shadings when certain thresholds are met of horizontal and vertical measurements (see Table 1). Work plane illuminance (E) has been found to capture user dissatisfaction with indoor lighting, specifically when addressing paper-based tasks (Van Den Wymelenberg and Inanici 2014). It also found as a principal parameter that prompts occupants to interact with shading devices (Van Den Wymelenberg 2012) with different set points suggested in the literature e.g., 1 klx (IESNA 2012; Katsifaraki et al. 2017) to 2 klx or above (Tzempelikos and Shen 2013; Konstantzos et al. 2015; Chinazzo et al. 2017). In architectural design studios particularly, direct horizontal illuminance of 1000 lx for at least 250 occupied hours ($ASE_{1000,250h}$) showed to have high correlation coefficient to students' dissatisfaction (Shafavi et al. 2020). It should be noted, however, that some individuals may accept high horizontal illuminance (e.g., 5000 lx), and only the most extreme cases can be confidently identified as uncomfortable (Van Den Wymelenberg and Inanici 2014). Other study found that the mean global vertical exterior illuminance at windows of 41 klx has commonly triggered manual blinds occlusion (Sutter et al. 2006). Different threshold has been suggested by Reinhart 2003 for blinds occlusion of 50 klx (Reinhart 2003). Nezamdoost et al. 2017 found that a significant percent of blinds occlusion took place when exterior vertical illuminance exceeds 40 klx (Nezamdoost and Van Den Wymelenberg 2017). Between exterior and interior illuminance data, the latter may provide a consistent measure to trigger shadings closing since it fundamentally counts façade designs and materials that would affect the internal environment and users' interactions, unlike exterior measurements.

Vertical eye illuminance (E_v) was also found to predict and evaluate visual discomfort in various daylit conditions. It was found that vertical eye illuminance E_v (view direction parallel to windows) above 1250 lx can cause visual discomfort (Van Den Wymelenberg and Inanici 2014). Higher vertical eye illuminance thresholds >1500 lx was suggested by Jakubiec et al. which identified high percentage of occupants discomfort (Jakubiec et al. 2015). Converging threshold (E_v >1700 lx) was suggested by Karlsen et al. which was associated with blinds activation (Karlsen et al. 2015). Bian and Luo found a much higher vertical eye illuminance threshold of visual discomfort at 3000 lx or above (Bian and Luo 2017). E_v was also found in some cases to better describe users' visual satisfaction/ dissatisfaction from their perspective over the horizontal illuminance data, except for the cases that address horizontal tasks (Van Den Wymelenberg and Inanici 2014).

Luminance-based glare metrics have been also developed to describe visual discomfort in the luminous environment that trigger shading control (Van Den Wymelenberg and Inanici 2014). In detail, shading occlusion has been commonly correlated to glare indices such as Daylight Glare Index (DGI), specifically when a DGI more than 20 is received (Lee and Selkowitz 1995; da Silva et al. 2012; Oh et al. 2012; Singh et al. 2016). Nevertheless, it is argued that DGI is not an ideal determinant of discomfort in daylit spaces except under controlled conditions when direct light or specular reflections are not present in a field of view (Jakubiec and Reinhart 2011; Hopkinson 1972). Alternatively, the index of Daylight Glare Probability

(DGP) (Wienold and Christoffersen 2006) has been recently used as an indicator for discomfort glare (Wienold and Christoffersen 2006; Jakubiec and Reinhart 2012) and also found to outperform the DGI (Van Den Wymelenberg and Inanici 2014). DGP provided a good correlation to discomfort glare subjectively assessed by occupants (Wienold et al. 2019; da Silva et al. 2012), and it was adopted for many shading occlusion scenarios (Jakubiec and Reinhart 2012; Wienold et al. 2011; Wienold 2007). According to Wienold, DGP has four thresholds: imperceptible glare= $DGP \leq 0.35$; perceptible glare= $0.35 < DGP \leq 0.40$; disturbing glare= $0.40 < DGP \leq 0.45$; intolerable glare= $DGP > 0.45$ (Wienold 2009). DGP was assumed to trigger shading occlusion when DGP exceeds 0.35 (Wienold 2007; Wienold et al. 2011), or 0.40 (Jakubiec and Reinhart 2012), based on DGP ratings proposed by Wienold (Wienold 2009), see Table 2. In architectural design studios particularly, spatial visual discomfort $DGPs_{\geq 0.45}$ for >20% of the occupation time showed high correlation coefficient to visual dissatisfaction with indoor daylight when compared with architectural students' evaluations (Shafavi et al. 2020).

2 Case Study

The selected case study is the building of the Faculty of Engineering at Al-Azhar University (girls' campus) located in Cairo, Egypt (30.04° N, 31.23° E). Based on the weather data of Cairo city obtained by *Climate Consultant 6.0* (Liggett et al. 2016), the annual average cloud cover is less than 20% and the annual average of direct illumination is over 35000 lx.

The building has an approximate area of 2680 m^2. Four architectural design studios are currently used which face the following orientations: south-west and north-east (studio A) north-west (studio B), south-east (studio C), and north-west (studio D) (see Figure 1). The studios have WWR of about 30% with a double-pane clear glazing windows ($T_{visible}$= 77 %). In these design studios, horizontal desktops are the main visual target for manual drawings, model making, and reading/writing (the latter mostly during exams). Additionally, the studios are also used for lectures where the front whiteboard is the main visual target.

A 4-storey extension building was designed to be connected directly to the existing building with an estimated area of 1845 m^2. To increase the capacity of the architectural department, eight studios (2 studios per floor, E and F) were allocated in the new extension building, facing the south-west and the north-east directions (see Figure 3). The current architectural studios (A, B, C, and D), on the other hand, were planned to be used for other administrative purposes. Due to building permits inside the campus, windows' height was kept at same level as the existing building as well as window-to-wall ratio (WWR) of 30%. The defined WWR also complies with research findings in the literature to reduce glare risk and to improve indoor daylight and energy performance (Berardi and Anaraki 2018; Sherif et al. 2014). Internal material finishing almost kept similar as the existing building.

3 Problem Identification

In the existing building, visual discomfort from daylight was identified as an issue among the students in the architectural design studios during the educational year. This leads them to either closing the internal drapes most of the time (if installed), even when natural ventilation is highly needed, or using primitive solutions such as putting papers/drawing boards to block direct sunlight (see Figure 2). To further understand the issue, a primary analysis was conducted. The students who study in the existing architectural studios were invited to an online survey, created with *SoSciSurvey.de* website, concerning their evaluations of daylight levels in terms of their intensity (using a rating scale), visual discomfort and glare occurrence from windows, and the type of activities they find difficulties while performing due to visual discomfort. The students were asked to consider the whole space over the entire year in their evaluations. The survey was given in Arabic as its their mother language and the English translation is presented in this paper, produced by a professional translator from the final Arabic version. The adequacy of the translation was confirmed by back-translation by a second translator (Table 3).

In total, 195 students took part in the study. All the participants are females (as the university campus is mainly for girls only), age between 18 and 26 years old. Incomplete data was not considered in the analysis. Besides, the data for studio A was excluded as the students rarely use this studio because of its limited capacity to host large classes compared to other studios. After filtering the data, 170 responses remained. In general, most of the students descried their daylighting levels from medium to strong (3 to 5) in all studios. This percentage increased in studio C (S-E orientation) compared to B and D (N-E and N-W orientations), specifically when describing strong daylighting levels (5). Overall, about 84 students (49%) reported that they have experienced visual discomfort issues. In detail, 33% and 42% of students have experienced visual discomfort from daylight in studios B (N-W orientation) and D (N-W orientation) respectively. This percentage was higher in studios C (S-E orientation) with about 73%. Because each student has no fixed seating location in the same studio over the academic year, the exact positions of the students who have/have not experienced visual discomfort could not be reported. For those who have experienced visual discomfort issues, 32% agreed to have difficulties in performing all the task, while 46% find difficulty when looking at the front whiteboards specifically, compared to 17% who have visual discomfort issues only while using the laptops. On the other hand, only 5% of students have experienced discomfort only when performing horizontal based tasks. Interestingly, the general comments received from the students expressed more as number of them explained to experience visual discomfort specifically '*when seating close to windows'*. Others wrote 'I *cannot read on the white boards because of the glare'*. Other complained that '*glare occurrence usually causes fatigue sensation and headache while I'm drawing'*. The survey results are presented in Figure 4.

The survey results generally confirm the observations in Figure 2 for visual discomfort being an issue for a considerable percentage of students in the architectural studios, particularly in the south-east orientation. Based on the performed activities, visual discomfort was detected for multiple visual targets, mostly vertically towards the whiteboard. Backing by these analyses, it was important to consider students' visual environment while designing the new extension building, where visual discomfort is likely to be an issue in the architectural studios (i.e., E and F), specially with the similarities in WWR and finishing materials.

In order to address the expected visual discomfort issues from daylight, this study proposes an evaluation method that employs visual discomfort-based analyses to drive façade shading design, aiming at protecting against visual discomfort received for multiple visual targets in the architectural studios. To achieve this aim, several visual discomfort indicators were used from the very beginning and a simulation workflow was proposed, considering all seating/view positions, to drive the shading design solutions and to support decision making. The objective of the evaluation method is to minimize number of hours where visual discomfort from daylighting is expected, taking into account possible horizontal and vertical visual targets, while maintaining adequate daylighting levels for students' activities during the year.

The following sections present in detail the proposed shading solutions, the selected visual discomfort indicators, and simulation process.

4 Methodology

4.1 Visual Discomfort Indicators

Large percentage of students' responses revealed that visual discomfort is a considerable issue particularly when looking at front whiteboards and computers screens. To capture the possibility of glare occurrence when looking towards the vertical visual targets in the architectural studios E and F, vertical eye illuminance measured at a seated human was used at a threshold of 1700 lx ($E_{v>1700\ lx}$). This threshold was selected based on Karlsen et al. (Karlsen et al. 2015) which was found to likely disturb the users, leading them to activate the blinds when performing vertical based tasks (e.g., using computers). It is also convergence to other threshold (i.e.,1500 lx) suggested in the literature to predict user visual discomfort for view positions parallel to the window (Jakubiec et al. 2015). In addition to vertical eye illuminance, the luminance- based glare metric DGP was used to detect visual discomfort for vertical view targets since it has been found to be the most robust metric to model glare occurrence for side-lit spaces under daylight conditions (Wienold et al. 2019). The DGP has been used extensively in simulation studies evaluating complex and scattering façades (Wienold et al. 2011; Jakubiec and Reinhart 2012) and showed high correlation coefficient to visual dissatisfaction with indoor daylight when compared with architectural students' evaluations (Shafavi et al. 2020). In this study, the threshold of visual discomfort was set whenever $DGP \geq 0.4$ (disturbing glare) is received.

In addition to $E_{v>1700\ lx}$ and $DGP_{\geq 0.4}$, horizontal illuminance at desktop level was used in this study to predict visual discomfort from daylight on desktops while performing horizontal-based tasks at a threshold of 2000 lx ($E_{>2000\ lx}$) based on Tzempelikos and Shen 2013, Konstantzos et al. 2015, Van Den Wymelenberg and Inanici 2014. The three indicators of $E_{>2000\ lx}$, $E_{v>1700\ lx}$ and $DGP_{\geq 0.4}$ were selected together in the study as they represent good proxy to capture discomfort glare for both vertical and horizontal visual targets, particularly with view directions parallel to windows (Shafavi et al. 2020; Van Den Wymelenberg and Inanici 2014; Wienold et al. 2019).

Lastly, in order to ensure that daylighting adequacy is not compromised while protecting against visual discomfort, annual daylight was calculated based on Spatial Daylight Autonomy (sDA). sDA reports the percentage of space that receives sufficient illuminance for at least 50% of occupied time. In this study, sDA was calculated through *ClimateStudio,* using IES LM-83 standards, and evaluated based on the threshold of 300 lx, since it showed high correlation with students' satisfaction in the architectural design studios (Shafavi et al. 2020).

4.2 Proposed Shading Systems

The proposed shading systems in this study are based on varies fixed and dynamic solutions (Figure 5). In detail, the study examined fixed shading systems of: light shelf, louvers, and solar screen, proposed previously in research studies and showed tangible improvements in controlling excessive lighting under clear-sky climates (Wagdy 2015; Ishac and Nadim 2021; Sherif et al. 2012; Abdelwahab et al. 2018). The dimensions of the proposed shading systems mostly comply with the recommendations in the literature, maintaining also the view to outside evidenced to enhance student learning rather than detracting it (Heschong and Mahone 2003). To provide additional control over visual discomfort conditions, smart windows' system with electrochromic dynamic glazing (i.e., switchable glazing devices that change colour electrically) was examined in this study to shade the window since it showed significant improvements in controlling daylight and glare compared to conventional double-glazed windows (Sullivan et al. 1994; Lampert 1998; Selkowitz et al. 1994).

4.3 Modelling and Simulation

Rhinoceros 7.0 and *Grasshopper (V.0.9.0076)* tools were used to model the existing and the new extension buildings of the Faculty of Engineering at Al-Azhar University (girls' campus). Annual daylighting and glare simulations were conducted using lighting modelling engine *RADIANCE 5.0* via the newly developed tool *'ClimateStudio'* for *grasshopper v1.1.7720.24392*. RADIANCE has been thoroughly validated and proven to produce reasonable accuracy compared to physical measurements (Reinhart and Walkenhorst, 2001). Light reflectance from interior surfaces, furniture, external wall thickness (0.5m) and glazing Visible Light Transmission were considered in the simulation calculations. Internal optical material properties are shown in Table 4. *Radiance* parameters values set as: ambient bounces = 6, and ambient sampling= 4096.

The new architectural studios were assumed to be occupied during the educational year as well as during the summer times for summer courses and workshops from 8am to 6pm, same as the occupancy schedule in the existing architectural studios. Studios E, F (Figure 3) have a dimension of 24 x 18.2m and a height of 4m. The openings have widths of 0.8m (small model) or 2m (large model) x2m height, and the window's sill level height=1m. Each studio was assumed furnished approximately with 78 standardized white drawing tables (0.92x1.27 m) to be used for manual drawing and serve as a tool for students so they can put the laptop and other items such as books, stationery, and materials/tools for model making and assembly. The drawing tables were located with a distance of 2 m between each seating position to maintain social distancing corresponding with the governmental orders to reduce the spread of contagious disease of COVID-19. This complies to the recent recommendations in the literature to keep a distance of 3 to 6 feet between the students (van den Berg et al. 2021), considering also students movement across the drawing table.

For annual glare analysis, all view positions of the 78 locations were considered and tested at a head height of 1.2 m (Konstantzos and Tzempelikos 2014). The studios were designed to be used as a whole area for large group of students. The layout can also be divided in two sub studios facing the front and the back whiteboards. Therefore, the view positions for E_v and DGP calculations were tested in both directions; forwards and backwards, to capture possible chances of glare occurrence. For annual daylighting analysis, the light sensors were placed on the centre of the drawing tables at height of 0.8m to measure horizontal illuminance where manual drawing, reading/writing and model making tasks are performed.

To control colour switch of the electrochromic dynamic glazing solution, the study proposes a simulation workflow that controls each window separately in accordance with the predefined visual discomfort criteria received in the nearest light sensor. This workflow is based on the pre-calculation of the selected indicators (i.e., horizontal illuminance, DGP, and vertical eye illuminance) for hourly time step during the year (3650 h), measured from seating/view positions close to the windows (with no shading installed), see Figure 6-left. Those seating/view positions were specifically considered because the sun is mostly in the field of view of the observer and severe visual discomfort conditions are more likely to occur. Whenever visual discomfort is predicted for horizontal visual target (using $E_{>2000\ lx}$) together with vertical visual target (using $E_{v>1700\ lx}$ or $DGP_{\geq 0.4}$, measured towards the front or back whiteboard) at any sensor, the closest window's glazing is controlled and switched accordingly, e.g., Sensor 1 (S1) controls window 1 (W1), sensor 2 (S2) controls window2 (W2), etc. (see Figure 6-right). To construct this logic, the 'IF' function was employed to define the occupation hours when visual discomfort is/ is not predicted for both horizontal and vertical visual targets-based on the specified criteria- at each sensor separately as follows:

If [E>2000 lx and {($E_{v\ front/back}$ >1700 lx) or ($DGP_{front/back}$ ≥0.4)}]

The returned value from this logic was converted to 1 (if true), or 0 (if false) for all occupation hours. Based on this, a shading schedule was generated- for each window separately- where (1) value means that dynamic glazing colour is switched on (the window is shaded), and (0) value means that dynamic glazing colour is switched off (the window is unshaded). The gnerated shading schedules were used in the next step to control the dynamic glazing for each window indevidually and conduct the final simulations accodingly. The simulation workflow proposed for the dynamic glazing and the detailed *grasshopper* script are shown in Figure 7.

5 Results and Discussion

5.1 Base Case

A preliminary annual daylight simulation analysis was conducted at first for the whole educational spaces (classrooms and studios) in the new extension building with no shading installed (shadings were assumed open 100% of time). The results showed that 100% of space receives at least 300 lx for at least 50% of occupied time in the architecture design studios (sDA), with average annual illuminance 2550 lx (see Figure 8).

In case of architectural studios E and D specifically, the average of annual horizontal illuminance, calculated at tables' positions, reached 3250 lx (sDA=100%). On the other hand, annual glare analysis measured from the perspective of the 78 view positions (forward and backwards to the whiteboards) showed high risk of glare occurrence (about 20% of the views received disturbing glare (DGP$\geq$ 0.40) for > 20% of occupation time), particularly those who seat close to the windows, see Figure 8. This coherently agrees with the students' comments collected in the existing architectural studios located on the same site. Since the data obtained for studios E and D was relatively close, the analysis of the results is presented in the following sections only for studio E, referred as 'base case'. To focus more on the high-risk seating/view points close to the windows, the results of the visual discomfort indicators were presented and discussed mainly for those positions.

In the south-west façade (SW), the percentages of occupation hours when average $E_{>2000\ lx}$, $E_{v>1700\ lx}$ and $DGP_{\geq 0.4}$ exceeded the thresholds were 83% (3023 h), 84% (3047 h) and 37% (1341 h) respectively, specifically for the seating/view points close to windows. For the opposite points close to the north-east façade (NE), the percentages of occupation hours when $E_{>2000\ lx}$, $E_{v>1700\ lx}$ and $DGP_{\geq 0.4}$ exceeded the thresholds were, 57% (2091 hours), 71% (2580 h), and 13% (455 h) respectively. These results clearly suggest visual discomfort being an issue for a considerable amount of time during the year, particularly in the south-west facade. In general, the defined thresholds of horizontal and vertical eye illuminance showed a good agreement in predicting visual discomfort for about 82% (SW) and 57% (NE) of occupation time, while the threshold of DGP met the other thresholds for a less amount of occupation hours 37% (SW) and 13% (NE).

5.2 Fixed Shading

Figure 9 presents annual simulation results of daylight and glare when the fixed shading design solutions: light shelf, louvers, and solar screen were installed individually. For the same shading systems, Figure 10 shows the number of occupation hours that exceeded the thresholds of $E_{>2000\ lx}$, $E_{v>1700\ lx}$, and $DGP_{\geq 0.4}$ (received in the seating/view points close to window) in comparison to the base case (with no shading installed). In general, Figure 9 shows that the proposed fixed shading systems ultimately lowered the average annual horizontal illuminance to almost half compared to the base case, although yet, daylight levels are adequate ($sDA_{300\ lx}$=100%). Moreover, the proposed fixed shading solutions dropped hourly $DGP_{\geq 0.4}$ values below the threshold for most of the occupation hours. Average $E_{>2000\ lx}$, $E_{v>1700\ lx}$, however, remained over the visual discomfort thresholds for a considerable number of occupation hours (see Figure 10).

In detail, the light shelf shading system ultimately decreased the amount of time where disturbing glare was received. As such, hourly $DGP_{\geq 0.4}$ values dropped below the threshold for almost whole occupation time in both south-west and north-east facades (less than 5% of occupation hours receives disturbing glare). However, the system did not completely control the amount of light received on the horizontal desks close to windows in the south-west façade which yet received $E_{>2000\ lx}$ for 64% of occupation time (2319 h). The calculations of $E_{v>1700\ lx}$ led to higher percentages in the same orientation. Both criteria combined exceeded the thresholds for a considerable time in the south-west façade, i.e., 62% (2251 h). The light shelf shading system performed better in the north-east façade as it reduced the occupation time when $E_{>2000\ lx}$ and $E_{v>1700\ lx}$

exceeded the thresholds to 29% (1047 h) and 35% (1295 h) respectively, which represents almost half of the occupation hours receiving $E_{>2000\ lx}$ and $E_{v>1700\ lx}$ in the base case (see Figure 10).

Similar to the light shelf solution, the louvers shading system reduced the percentage of hours receiving $DGP_{\geq 0.4}$ on the points close to windows (7% -SW, and 2% -NE). In the north-east facade, using the louvers system evidently cut the percentage of occupation time when $E_{>2000\ lx}$ and $E_{v>1700\ lx}$ exceeded the criteria to a third compared to the base case, although the percentage of the equivalent hours remained relatively high in the south-west façade as both indicators met the specified thresholds for 43% and 59% of occupation time respectively. Both criteria combined met the thresholds for 42% of occupation time (1530 h).

The solar screen solution decreased the average of annual horizontal illuminance (1491 lx) across the whole floor area compared to the light shelf and louvers systems, although the measured data remained relatively high, particularly for those are close to the south-west façade (see Figure 9). For these points, $E_{>2000\ lx}$ exceeded the defined threshold for 48% of occupation time (1735 h), whereas $E_{v>1700\ lx}$ exceeded visual discomfort threshold for 64% of occupation time (2329 h). Both criteria combined met the thresholds for 45% of occupation time (1629 h). The solar screen had a better performance in the north-east façade as it evidently decreased the occupation time when $E_{>2000\ lx}$ and $E_{v>1700\ lx}$ exceeded visual discomfort thresholds (687 h and 855 h respectively). The analysis also showed that using the solar screen had less control over $DGP_{\geq 0.4}$ compared to the other shading solutions as 10% (378h) of occupation time still receive disturbing glare in the south-west facade (see Figure 10).

In general, the results show that all the proposed shading systems led to better performance compared to the base case although it varied in controlling visual discomfort based on the selected criterion. The light shelf shading system showed to provide the best control over the disturbing glare received compared to the other shading systems, although the occupation time receiving $E_{>2000\ lx}$ and $E_{v>1700\ lx}$ remained considerably high, particularly in the south-west façade. The solar screen shading system slightly improved the performance in terms of horizontal and vertical eye illuminance, although there was still a large percentage of occupation time when $E_{>2000\ lx}$ and $E_{v>1700lx}$ exceeded the specified thresholds in the south-west facade. The louvers system on the other hand outperformed the solar screen system as it reduced the occupation time receiving visual discomfort criteria $DGP_{\geq 0.4}$, $E_{>2000\ lx}$ and $E_{v>1700\ lx}$, particularly in the south-west façade. Among the proposed shading systems, using the louvers system led to less amount of time when the three indicators together exceeded the specified visual discomfort criteria. Figure 11 illustrates in detail the performance of the louvers system compared to the base case in terms of the average E, E_v, and DGP received for the whole occupation time. Beside the evident reduction in occupation time receiving discomfort criteria compared to the bases case, the figure also shows a consistency between illuminance data ($E_{>2000\ lx}$ and $E_{v>1700\ lx}$) in predicting visual discomfort for both cases.

5.3 Electrochromic Glazing

Figure 12 shows annual simulation results of daylight and glare when using the electrochromic glazing controlled via the proposed simulation workflow presented in section 4.3. Using the dynamic glazing led to operation rate of shading varied based on window's location (i.e., W1, W2, W3, etc.) between 50% to 82% of occupation time in the south-west façade and 50% to 70% in the north-east facade. In general, the electrochromic glazing system dramatically lowered illuminance received on the desktops compared to the base case (average annual illuminance =1027 lx), see Figure 13. As such, only 10% (north-east) and 30% (south-west) of occupation hours received $E_{>2000\ lx}$ compared to 57% and 83% in the base case respectively. Also, only 7% of the views received disturbing glare ($DGP_{\geq 0.40}$) for > 20% of occupation time. Despite of the reduction in indoor illuminance, annual daylight levels remained sufficient across total floor area ($sDA_{300\ lx}$ =100%).

Despite of the reductions in horizontal illuminance, the measured data of $E_{v>1700\ lx}$ was still over the defined threshold of for a considerable occupation time (66% in the south-west and 30% in the north-east façade). This can be seen in Figure 13 which generally shows that there were slight reductions in the occupation time receiving $E_{v>1700\ lx}$, and $DGP_{\geq 0.4}$ compared to the base case. This indicates that, although the controlling scenario was designed to shade each window separately based on the data received on the nearest seating/view position, it did not completely protect against visual discomfort for vertical view targets, based on $E_{v>1700\ lx}$, and $DGP_{\geq 0.4}$ criterion, which might be vertically received not only from the nearest window but also from other windows' directions. Using darker glazing tint to shade the window would lower E_v, and DGP data. However, this was not considered in this paper as it greatly compromised daylight availability (based on sDA indicator), and there were no tangible improvements in E_v and DGP results in return.

5.4 Combined Shading Solution

The interpretation of results in the previous sections showed that dynamic glazing dramatically lowered occupation time when high indoor illuminance $E_{>2000\ lx}$ received on desktops. Fixed shading systems, on the other hand, offered better protection against visual discomfort for vertical targets as it reduced occupation time receiving $DGP_{\geq 0.4}$ and yet it showed to slightly lower the percentage of hours receiving $E_{v>1700\ lx}$, specifically when using the solar screen and the louvers shading systems. A combined shading system of louvers system with electrochromic dynamic glazing was proposed accordingly to provide possible protection against visual discomfort for both horizontal and vertical visual targets. The results of annual daylight and glare simulations of the combined shading solution are presented in Figure 14 and Figure 15.

The results show that the combined solution ultimately lowered average horizontal illuminance across the whole floor from 3252 lx to 547 lx compared to the base case, although however annual daylight levels remained adequate across total floor area ($sDA_{300\ lx}$ =98.7%), see Figure 14. Annual glare analysis on the other hand generally showed a reduction in disturbing glare received in all view positions as none of the examined view position received disturbing glare ($DGP \geq 0.40$) more than 20% of occupation time.

For the examined discomfort criteria specifically, the analysis showed that $E_{>2000\ lx}$ exceeded the threshold for less than 9% in the south-west façade and less than 2% of occupation time in the north-east, showing a dramatic improvement compared to the base case (83% SW, and 57% NE). $DGP_{\geq 0.4}$ exceeded the threshold for less than 3% of occupation time in both facades. The received $E_{v>1700\ lx}$ exceeded the threshold for higher percentage of occupation time (19% in the south-west façade and 10% in the north-east).

Figure 15 shows in detail the occupation time when $E_{>2000\ lx}$ together with $DGP_{\geq 0.4}$ (left) and $E_{v>1700lx}$ (right) remained over the specified thresholds when using the combined shading solution compared to the base case. In the south-west façade, both $E_{>2000\ lx}$ and $DGP_{\geq 0.4}$ exceeded the thresholds for less than 3% (113 h) compared to 37% (1341 h) in the base case. Also, there was less than 8% of occupation time (300 h) where $E_{>2000\ lx}$ together with $E_{v>1700\ lx}$ exceeded the defined thresholds compared to 82% of occupation time (2973h) in the base case. In the north-east façade, the percentage of occupation time where $E_{>2000\ lx}$ together with $DGP_{\geq 0.4}$ or $E_{v>1700\ lx}$ exceeded the thresholds was lowered to less than 2% of occupation time, showing again significant improvements compared to the base case.

6 Conclusion

Despite of the large number of studies in the literature sought to improve daylighting performance through façade shading design under hot clear sky climates, there are still gaps lying in understanding and addressing the associated visual discomfort issues, known also to negatively impact students' productivity and wellbeing. This paper presents a case study of the architectural design studios at Al-Azhar University in Cairo- girls' campus, where visual discomfort from daylight was identified and reported by the students to affect their visual comfort for multiple horizontal and vertical visual-based activities (e.g., looking toward the whiteboards, using their laptops, and using the drawing tables). In response, visual discomfort-based analyses were used in this study to drive façade shading designs in two-sided architectural studios, parallel to the window, aiming at protecting against visual discomfort. Multiple visual targets (horizontal and vertical, towards the front and back directions) were considered with all possible seating/view positions. The examination includes the evaluation of fixed and dynamic shading systems. For the latter and to precisely control the causes of visual discomfort continuously change throughout the course of the year, this paper has offered a simulation workflow tailored to shade each window individually based on the specified visual discomfort criteria received in the nearest seating/view position. The results showed that:

- The visual discomfort thresholds of horizontal and vertical eye illuminance ($E_{>2000\ \mathrm{lx}}$ and $E_{v>1700\ \mathrm{lx}}$) proposed to predict visual discomfort in this study generally showed a good agreement in terms of their presence during occupation time for most of the cases. $DGP_{\geq 0.4}$ met the other thresholds for much less occupation time. This suggests that illuminance data, based on the specified threshold, maybe more permissive in predicting visual discomfort compared to DGP under clear skies.
- The fixed shading systems proposed in this study (light shelf, louvers, and solar screen) evidently reduced the occupation time where visual discomfort is expected, compared to unshaded windows, particularly for vertical visual targets based on $DGP_{\geq 0.4}$ indicator. The percentage of occupation time receiving disturbing glare ($DGP_{\geq 0.4}$) was reduced from 37% to 3%-10% (based on shading type) in the south-west orientation, and from 13% to 2% or less in the north-east orientation compared to the base case. However, it showed to have less control over visual discomfort criterion based on horizontal and vertical eye illuminance ($E_{>2000\ \mathrm{lx}}$ and $E_{v>1700\ \mathrm{lx}}$).

- The simulation workflow proposed in this study to control dynamic electrochromic windows has led to significant improvements in protecting against visual discomfort specifically for horizontal view targets as only 10% (north-east) and 30% (south-west) of occupation hours received $E_{>2000\ \mathrm{lx}}$ compared to 57% and 83% respectively in the base case.
- To further improve shading performance, a combined shading solution was proposed which combines fixed louvers system with the dynamic electrochromic glazing system which successfully lowered occupation time receiving visual discomfort based on $E_{>2000\ \mathrm{lx}}$ criteria from 83% to 8% in the south-west orientation and from 57% to 2% in the north-east orientation. Additionally, for vertical visual targets, occupation time receiving $E_{v>1700\ \mathrm{lx}}$ was reduced from 84% to 19% in the south-west and from 71% to 10% in the north-east orientation. Only 3% of occupation time received $DGP_{\geq 0.4}$ in the south-west and 1% in the north-east compared to 37% and 13% respectively in the base case. On the other hand, indoor daylight availability was sufficiently maintained ($sDA_{300\ \mathrm{lx}}$ =98.7%).

The outcomes of this case study could be widely used as a feedback tool in the future façade designs to predict and control causes of visual discomfort from windows for multiple view targets under hot- clear sky conditions. The proposed simulation workflow can be employed for other dynamic shading systems (dynamic internal blinds, dynamic venetian blinds, etc.) so that window's shade can be precisely controlled based on lighting data that reaches the nearest sensor/ seating position. Applying this simulation workflow, however, should be taken with caution since the resulted performance is dependent on material visible transmittance (T_{vis}) which in case of low T_{vis} (e.g., dark glazing tint), daylight availability can be greatly compromised. Finally, although the produced results were generated based on validated simulation engine (i.e., RADIANCE) supported by subjective survey and participative observation, further verification, however, will be considered in future studies to confirm the results with field-based measurements. Further developments to the proposed evaluation method can be discussed in future studies to incorporate the new advances in predicting visual discomfort and the involved indicators under similar climatic contexts. Moreover, further investigation can be implemented towards evaluating the proposed shading solutions from the life-cycle cost and life-cycle energy perspective.

7 Data Availability Statement

All data, models, and code generated or used during the study appear in the submitted article.

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9 Tables

Table 1 Illuminance data related to shading occlusion in the literature

Reference	**Description**	**Threshold**
(Sutter et al. 2006)	Mean global external vertical illuminance	41 klx blinds closed
(Reinhart 2003)	Average external vertical illuminance	50 klx blinds closed
(Nezamdoost and Van Den Wymelenberg 2017)	Vertical exterior illuminance	40-60 klx, 60-80 klx and 80-100 klx
(Van Den Wymelenberg 2012)	Vertical exterior illuminance	Occlusion increases above 20 klx up to 100 klx
(Katsifaraki et al. 2017)	Average horizontal and vertical illuminance	horizontal illuminance with high limit of 1 klx, Vertical illuminance with high limit of 3 klx
IES LM-83, 2012	Direct sunlight on work plane	More than 1 klx for 2% of the analysis points
(Tzempelikos and Shen 2013)	Work plane illuminance	2 klx
(Konstantzos et al. 2015)	Work plane illuminance	2 klx

Table 2 DGI and DGP thresholds of shading occlusion in the literature

Reference	**Description**	**Threshold**
(da Silva et al. 2012)	DGI	>20
(Oh et al. 2012)	DGI	>22
(Singh et al. 2016)	DGI	>22
(Wienold et al. 2011)	DGP	>0.35
(Jakubiec and Reinhart 2012), (Wienold 2007)	DGP	>0.40

Table 3 Questions of the online survey

	General introduction to the survey
Q1	The floor plan of the faculty of engineering (girls' campus) is attached, showing the architectural design studios. Please select the architectural studio where you study. • (A, B, C, or D)
Q2	In general, what is your evaluation of daylighting levels in this architectural studio? • Select from a scale 1 (poor lighting) to 5 (strong lighting)
Q3	Do windows in this studio cause visual discomfort issues or glare? • (Yes, No), Add comment?
Q4	If you have any visual discomfort issues, please describe the activities you have difficulty performing? • (Manual drawings, reading/writing, and model making, looking at the whiteboard, using laptop, or all the above)

Table 4 Optical material properties of the new extension building

Geometry	**Material visual properties used in this study**		
Glazing	Glazing Double Pane Clear: T visible= 77.4 %; Reflectance=50%		
Interior walls	White painted wall with a 70% reflectance		
Exterior wall	White painted exterior wall with a 71% reflectance		
Ceiling	White painted ceiling 89% reflectance		
Floor	Beige floor tiles with 57% reflectance		
External ground	Lambertian diffuser with 20% reflectance		
Computer screen	Self-luminance of screen = 250cdm^2		
Furniture	White table with 86% reflectance		
Shading	Light shelf	Louvers	Solar screen
	White paint with a 71% reflectance	Exterior louvers with a 54% reflectance	White paint with a 71% reflectance

	0.1% Rvis(spec)	0.6% Rvis(spec)	T visible=0%
Electrochromic glazing	Halio glazing with tint/shade T visible= 21.3%		

10 Figures

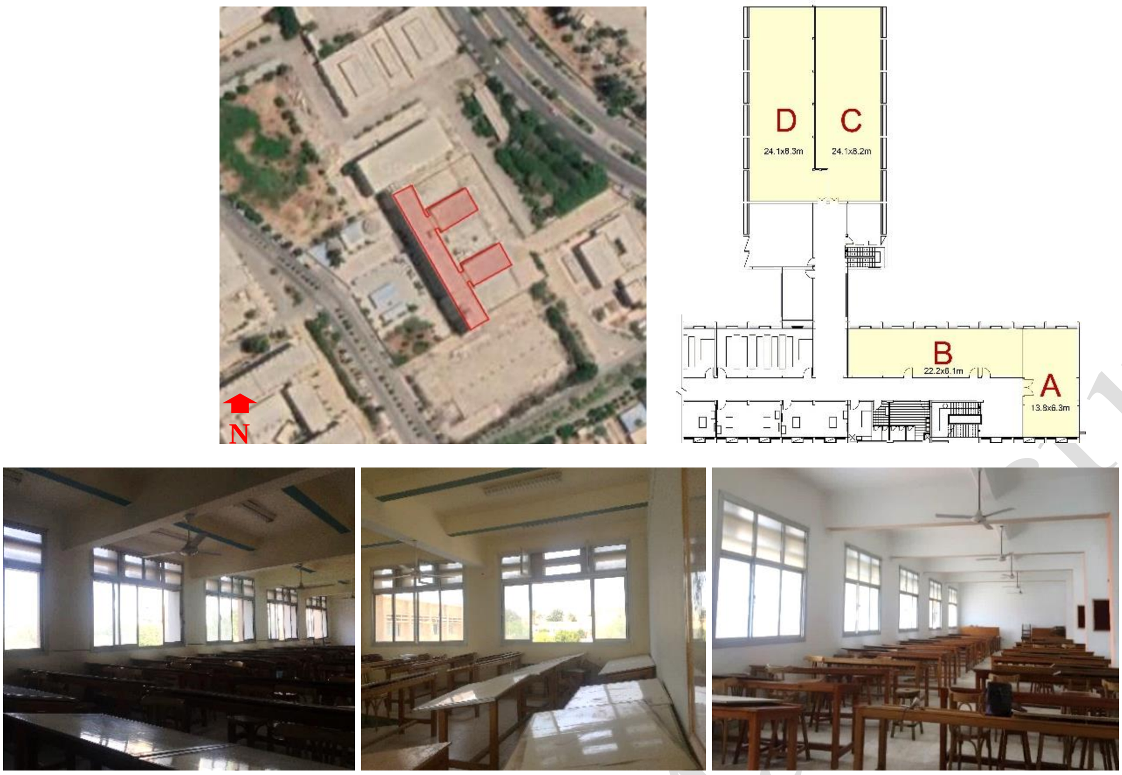


Figure 1 The existed building of Faculty of Engineering (girls branch) at Al-Azhar University, Cairo (top), Architectural studios B, C, and D (bottom)

Figure 2 Students blocking the sunlight from window using papers/drawing boards

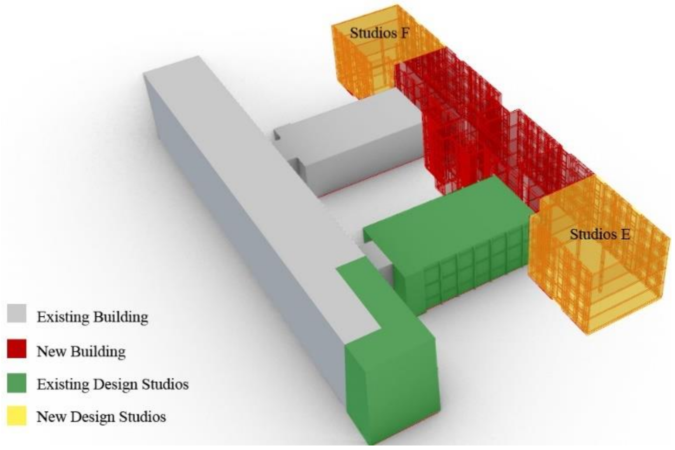


Figure 3 a 3D model shows the architectural studios locations in the existed building and the new extension building

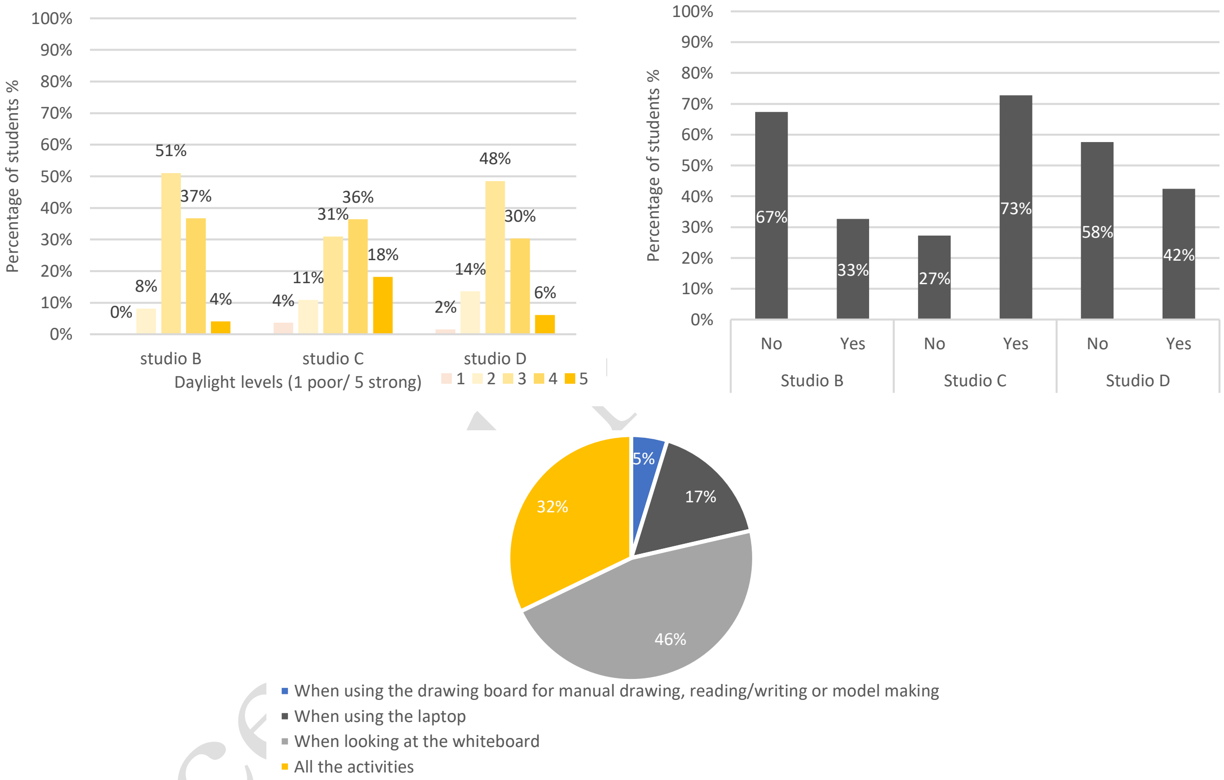


Figure 4 Students votes for indoor daylighting levels in studios B, C, and D (top left). the percentage of students who have (yes) and have not (no) experienced visual discomfort in studios B, C, and D (top right), The type activities they find difficulties while performing due to visual discomfort (bottom)

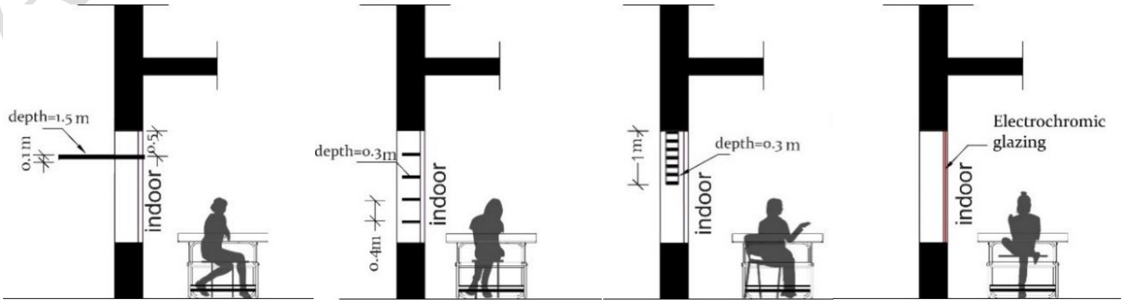


Figure 5 Shading systems proposed in this study: the light shelf, louvers, solar screen, and the electrochromic dynamic glazing

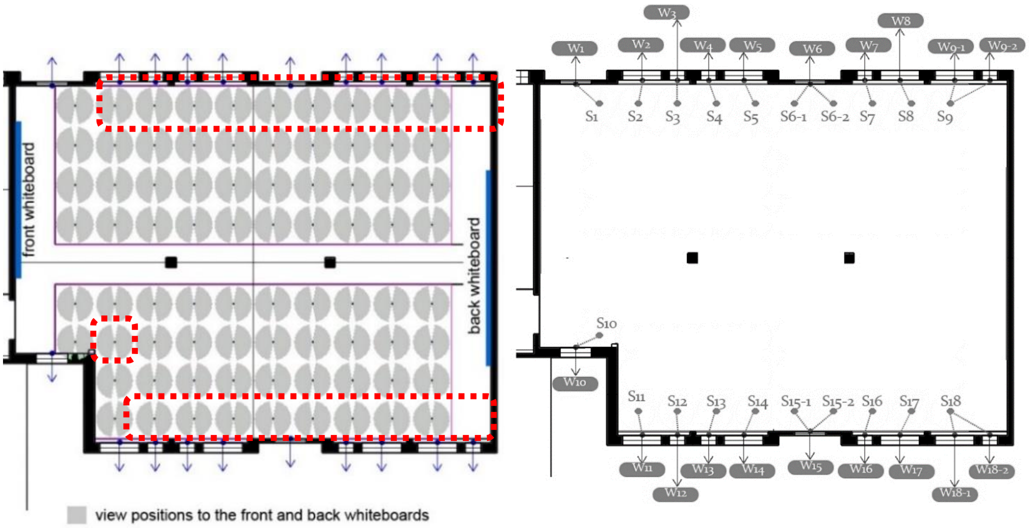


Figure 6 seating/view positions in the examined architectural studio showing points close to windows where visual discomfort is highly expected (left), the sensors controlling dynamic electrochromic glazing for each window (right)

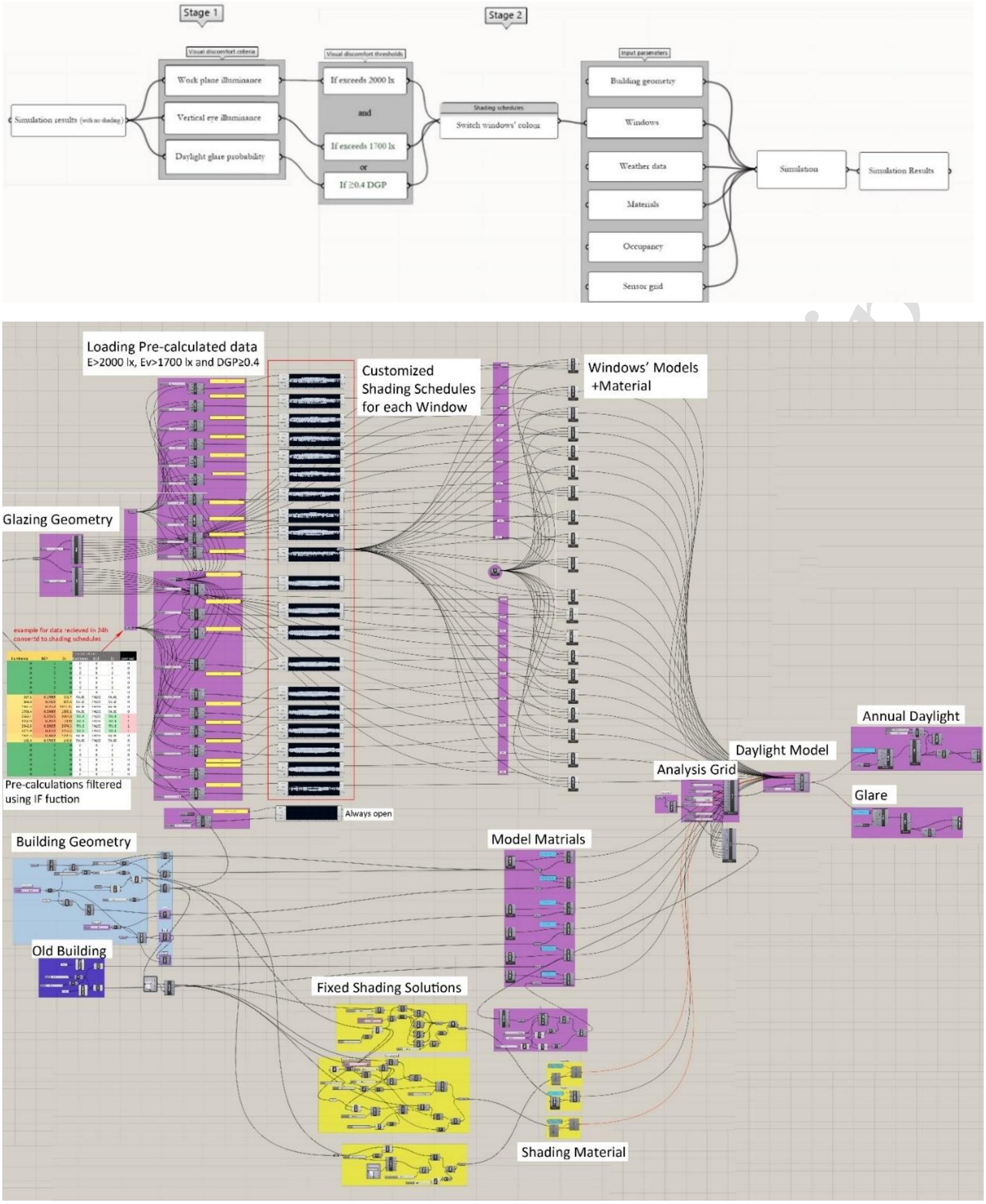
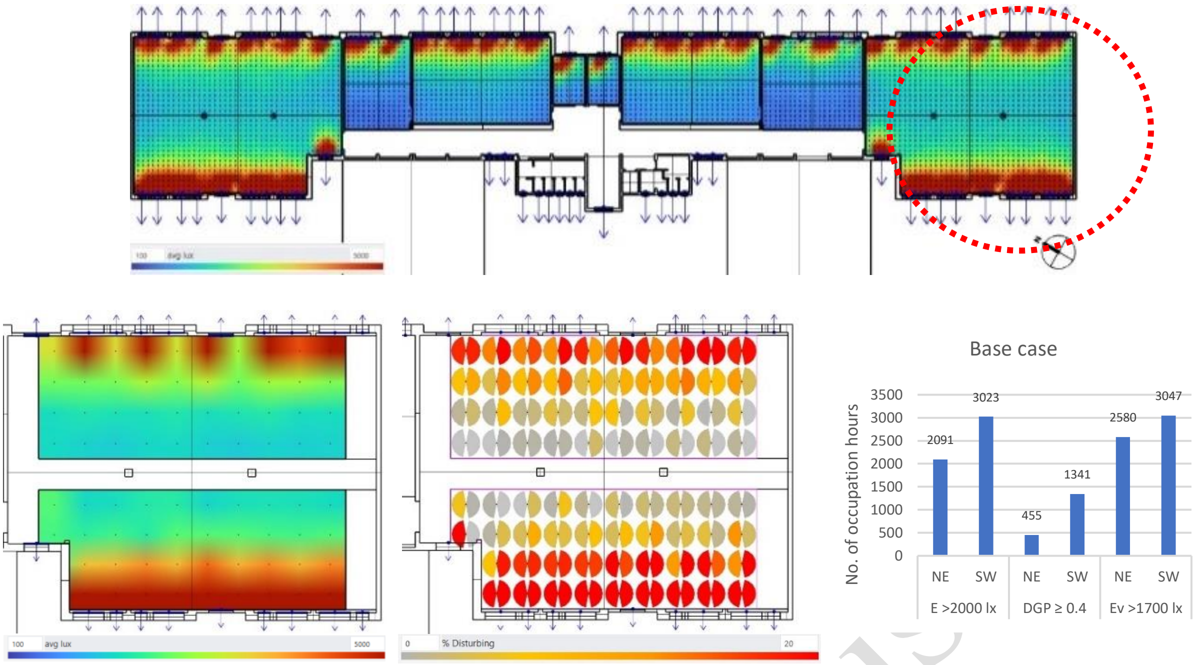


Figure 7 Simulation workflow proposed to control and estimate the performance of dynamic electrochromic glazing (top), Grasshopper script (Bottom)



Average illuminance= 3252 lx   Views with DGP$_{\geq 0.40,\ 20\%\ \text{(occupation time)}}$ = 20%

Figure 8 Illuminance levels in the new extension building (top), the colour maps for average horizontal illuminance and DGP> 0.4 >20% of occupation time in studio E (bottom left), no. of occupation hours where the threshold of E, E_v and DGP were met in seating/view positions close to windows (bottom right)

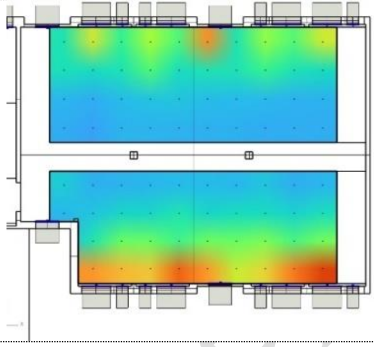
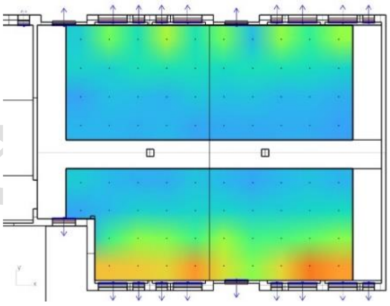
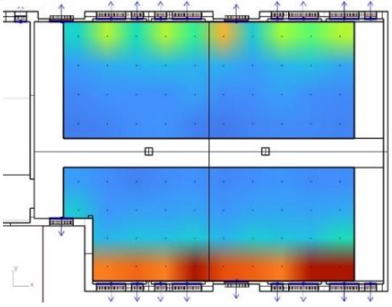
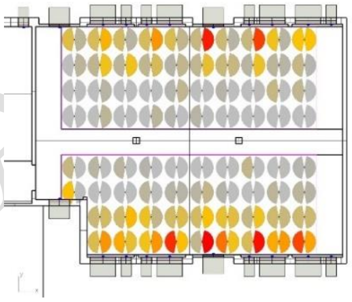
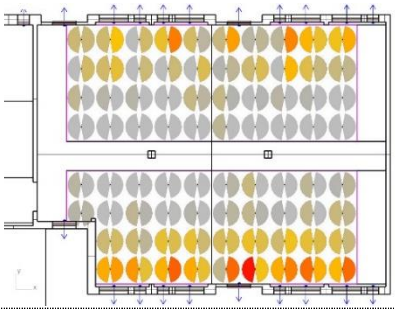
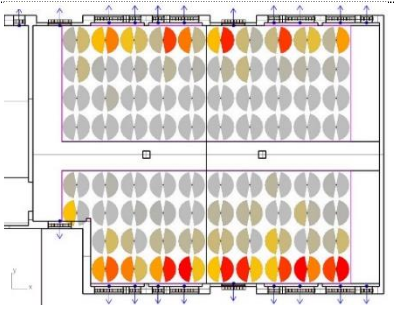
	Light shelf shading system	Louvers shading system	Solar screen shading system
Average annual illuminance			
	1794 lx- sDA=100%	1678 lx- sDA=100%	1491 lx- sDA=100%
%views with disturbing glare (DGP≥0.4) >20% of time			
	0.6%	0%	1.3%

Figure 9 Average horizontal illuminance and %views with DGP$\geq$ 0.4,> 20% of occupation time in the design studio E when using the proposed fixed shading systems: Light shelf, louvers, and solar screen

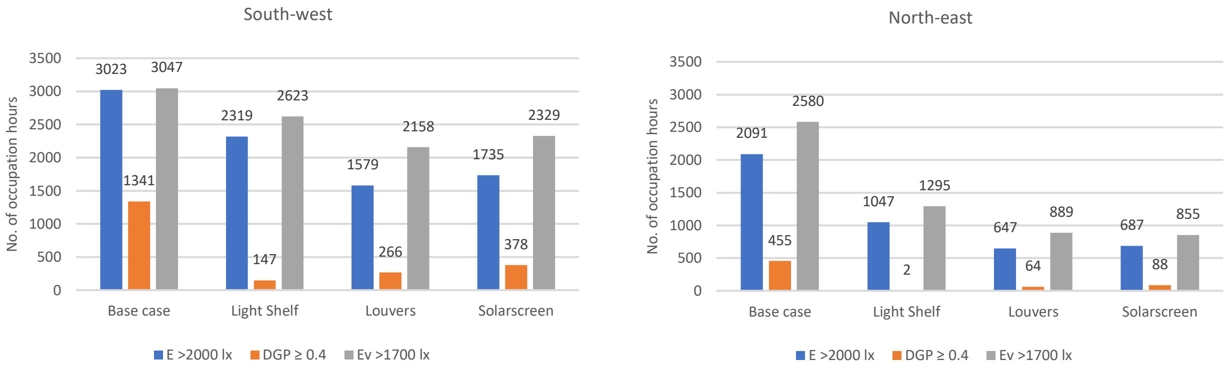


Figure 10 Number of occupation hours when average data met the visual discomfort thresholds $E_{>2000}$ lx, $E_{v>1700\ lx}$, and $DGP_{\geq 0.4}$ in the seating/view positions close to the south-west façade (left) and north-east façade (right)

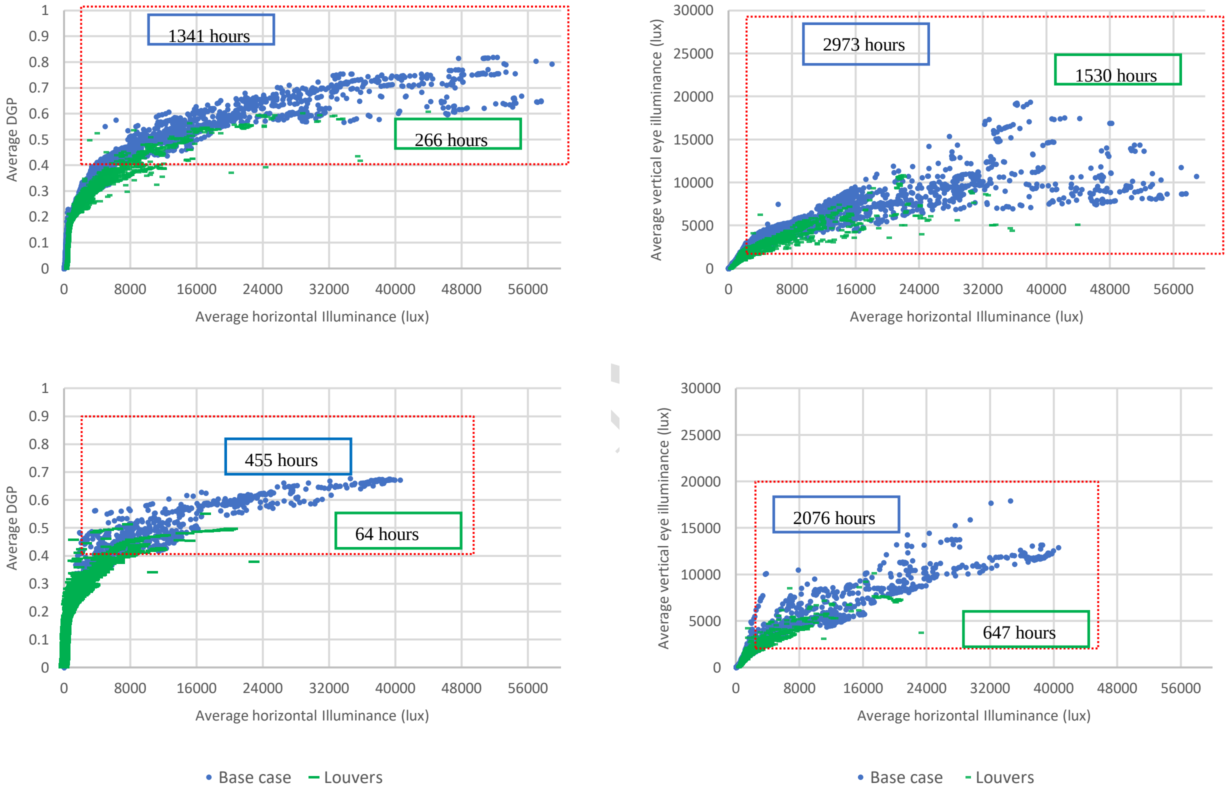
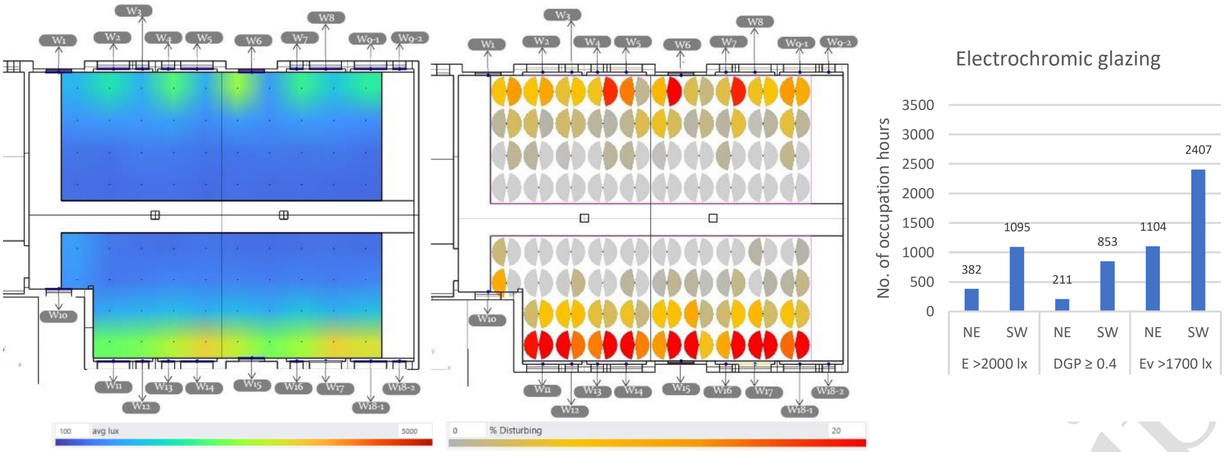


Figure 11 Hourly E and E_v, DGP received in the seating/view positions close to windows in the south-west (top) and north-east (bottom) when using the louvers system compared to the base case



Average illuminance 1027 lx- sDA=100%

Views with DGP$_{\geq 0.4,\ 20\%\ \text{(occupation time)}}$ = 7.1%

Orientation	Window no., Closing percentage									
North-east	W1= 49%	W2= 68%	W3= 55%	W4= 69%	W5= 62%	W6= 68%	W7= 64%	W8= 67%	W9-1= 68%	W9-2= 68%
South-west	W10= 50%	W11= 72%	W12= 71%	W13= 80%	W14= 80%	W15= 80%	W16= 79%	W17= 82%	W18-1= 72%	W18-2= 72%

Figure 12 Average horizontal illuminance and DGP $\geq$ 0.4, >20% of occupation time in the design studio E when using the dynamic glazing (top left-middle), no. of occupation hours where the threshold of E>2000 lx, E$_v$>1700 lx, and DGP ≥0.4 were met in seating/view positions close to windows (top right), closing percentage of occupation time for each window individually (bottom)

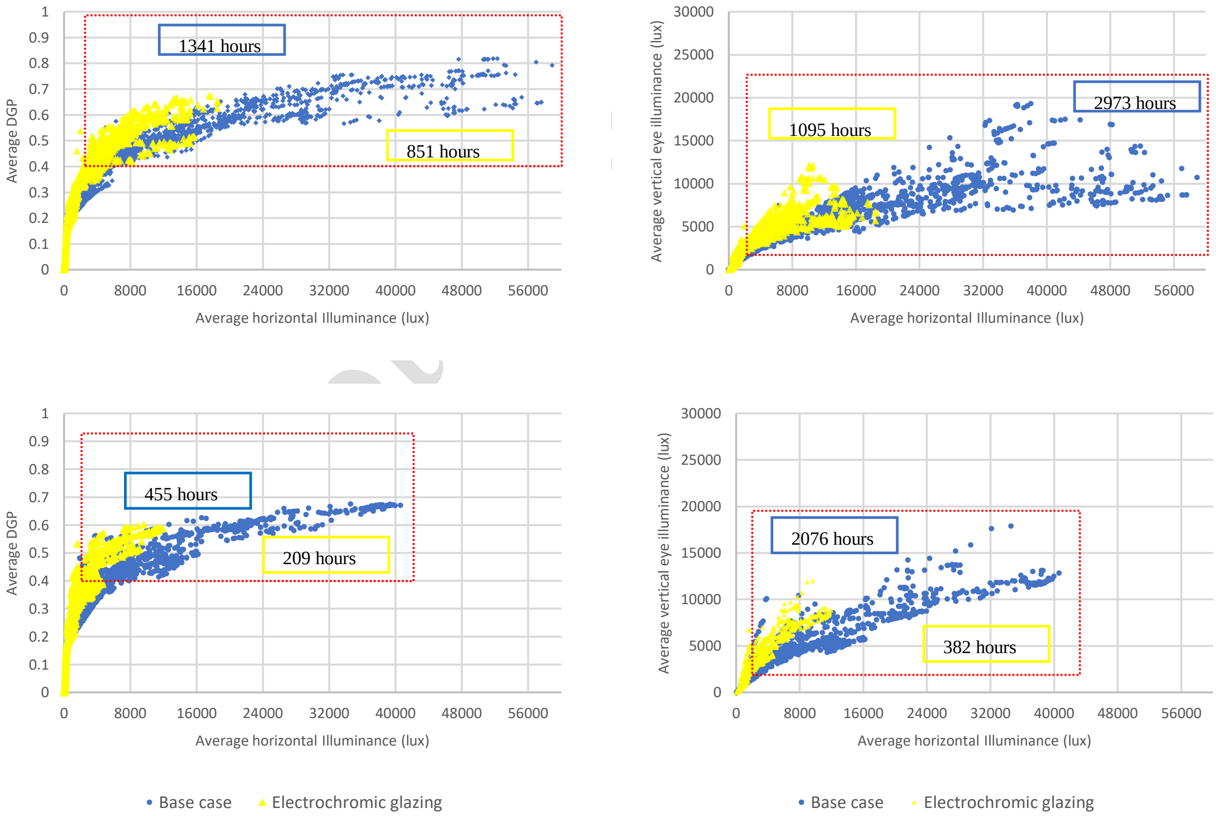
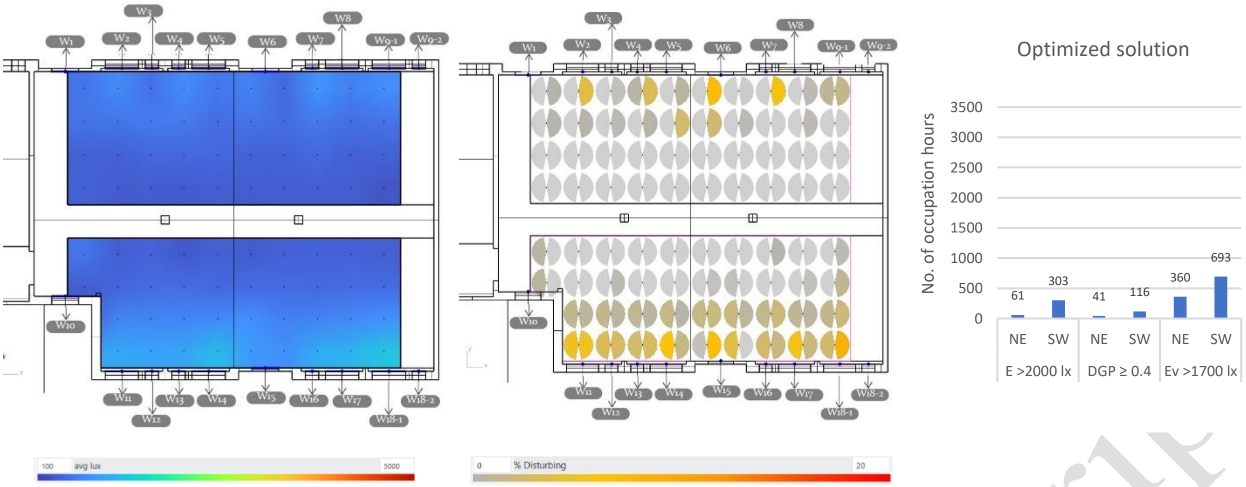


Figure 13 Hourly E and E$_v$, DGP received in the seating/view positions close to windows in the south-west (top) and north-east (bottom) when using the electrochromic glazing compared to the base case



Average illuminance 547 lx- sDA=98.7%

Views with $\text{DGP}_{\geq 0.4,\ 20\%\ (\text{occupation time})} = 0.0\%$

Figure 14 Average horizontal illuminance and %views with DGP≥ 0.4, >20% of occupation time in the design studio E when using the combined solution

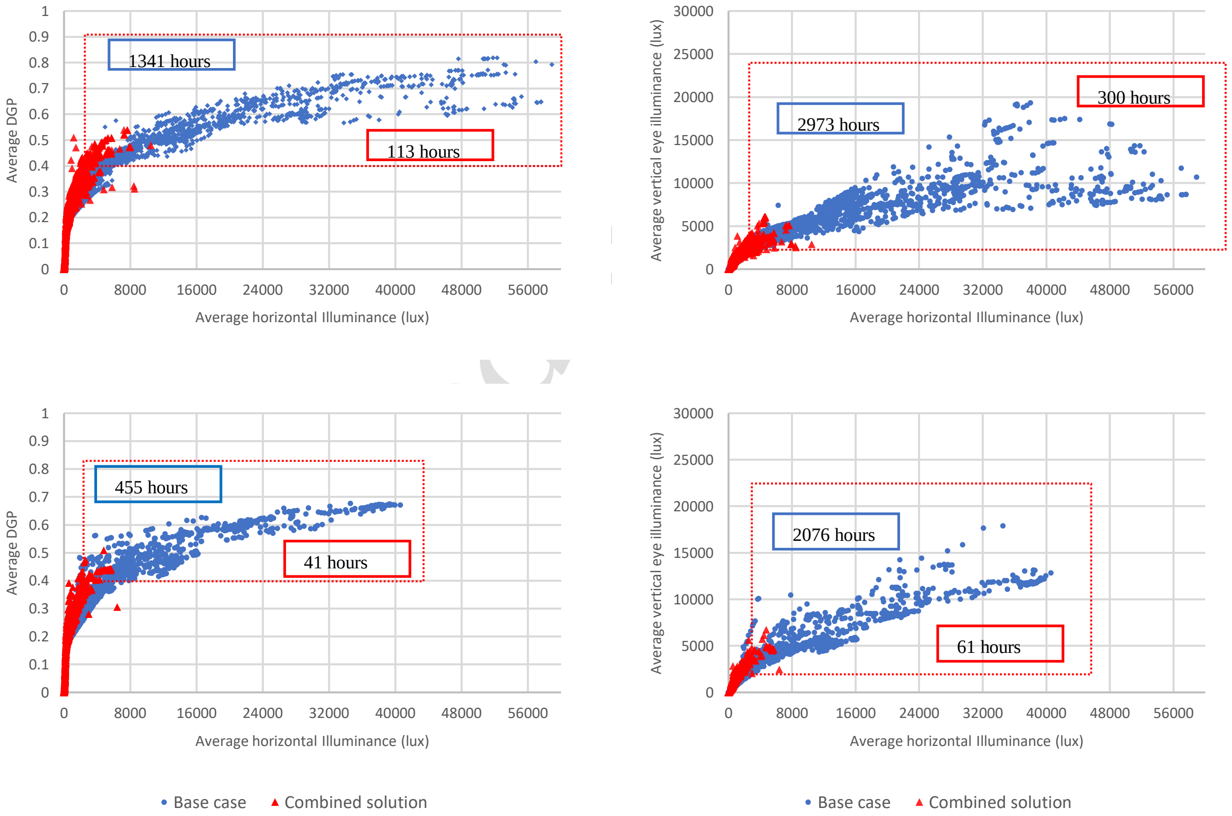


Figure 15 Hourly E and E_v, DGP received in the seating/view positions close to windows in the south-west (top) and north-east (bottom) when using the combined solution compared to the base case