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Semi-automated *vs* manually controlled dynamic facades: assessment through a field study on multi-domain occupant satisfaction

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ABSTRACT

Occupant satisfaction and acceptance with automated control strategies for dynamic façades is currently a barrier to the upscale of these systems. Building owners, designers and occupants are often unconvinced that an automated control strategy for dynamic façades could really be beneficial for building energy efficiency and occupant satisfaction. Previous work has indicated that an integrated multi-domain approach is required for capturing the influence of façades on occupants. The aim of this paper is to provide new knowledge on whether dynamic automated facades with user override (semi-automated) can outperform manually operated facades in terms of occupant multi-domain satisfaction. Occupant interaction, discomfort, satisfaction and indoor environmental quality were monitored in two different scenarios: one where the façade blinds were automatically controlled, aiming at maximising daylight and outdoor view access whilst mitigating glare, and one in which the façade blinds were manually controlled by the occupants. Results showed that when the façade was controlled by a semi-automated strategy, occupant satisfaction was higher (especially in the thermal environment), despite occupants reported a higher number of discomfort events due to lack of daylight and access to outdoor view. However, to increase occupant acceptance, a better prediction of occupant glare to prevent visual discomfort and maximise daylight and view is necessary.

1. Introduction

Automated controls of dynamic building components can improve buildings' energy efficiency and in turn significantly reduce the emissions from the built environment [1]. For instance, the automated control of dynamic façades could lead to large energy savings [2], whilst improving occupant satisfaction [3]. Their effectiveness depends on the level of responsiveness of the control system [4] and on occupant acceptance [5]. Occupant satisfaction and acceptance with automated dynamic façades have been investigated both in test chambers and in real environments [6], however the amount of current data and knowledge is often not considered sufficiently compelling by building owners, designers and occupants, to adopt automated dynamic façades. In particular, whether the stated energy efficiencies can realistically be achieved and whether this could be done without compromising and occupant comfort / satisfaction.

The automated control of façades is often reported to be disruptive and dissatisfactory for occupants, with occupant overrides as high as 88 % [7] in order to maintain access to outdoor view [8], or even to disable automated controls when possible [3]. One of the main reasons for occupant dissatisfaction with automated controls is the perceived lack of personal control that occupants experience when automated controls are implemented. The possibility for occupants to override automated controls (i.e. semi-automated control) has been shown to be pivotal for their acceptance and satisfaction with automated dynamic façades [3,9]. The ability of the control strategy to predict occupant visual comfort requirements was also reported as crucial for the acceptance of automated controls [10]. For instance, Attia et al. [11] showed that large majority of occupants were dissatisfied with automated controls because it was not able to mitigate glare and had a detrimental impact on daylight and outdoor view access. Similarly, Lee et al. [12] reported that access to outdoor view was the main driver for occupants to raise the blinds, while glare was the main driver for lowering them. However, other drivers such as privacy and thermal comfort can also play an important role and occupants expect automated controls to predict their demands [13]. Predicting these multi-domain

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demands is challenging, particularly because they are often in conflict (e.g. glare reduction *versus* access to outdoor view) [4]. As previously reported by Kelly-Waskett et al. [14], the refinement of automated control strategies according to occupant feedback and overrides is therefore key for the success of automated controls, since it allows to the control strategy to evolve and learn by assimilating actual requirements of the occupant. In addition, different controls per façade bay are required in the presence of large glazed areas because adjacent zones might have different requirements, for instance in terms of solar radiation.

Previous work by Luna-Navarro et al. [5] has shown that an integrated multi-domain approach is recommended for achieving occupant-façade satisfaction, wherein occupant requirements in all the four environmental domains (thermal, visual, air quality and acoustic) are simultaneously integrated with personal control and interaction. Whereas the previous work by the authors was performed in a test chamber for occupant-façade interaction studies, this present work investigates occupant integrated multi-domain satisfaction and interaction with dynamic façades in a real office environment. The control strategy was developed to include the following lessons-learnt from previous work, namely: (i) include the option for occupants to override automated control decisions; (ii) restore daylight and outdoor view access as soon as possible; (iii) prevent discomfort glare. The aim of this study is to gain evidence on: (i) whether a semi-automated control strategy that include these recommendations, can outperform a manual control in achieving higher occupant satisfaction for a given context; (ii) whether an integrated multi-domain approach is valuable when assessing façade influence on occupant environmental satisfaction and interaction in real office environments. This is achieved by collecting data on indoor environmental quality, occupant satisfaction and interaction in three different periods. In the first and the third period (first scenario), the façade was controlled by an automated strategy and occupants could always override the system, while in the second scenario, the façade had no automated control, but could be operated manually. The methodology adopted in this study is described in detail in Section 2. The results from the monitoring campaign the corresponding discussions are presented in Section 3 and section 4, respectively.

2. Methodology

2.1. Description of the case study

The field study was performed in an open-plan office in the city of Vittorio Veneto in the North-East of Italy. The occupants of this office space were employed in marketing, accountancy or desktop research and development roles. The office had a floor plan of 12 × 14 m^2 with a glazed double skin façade, more specifically a double skin façade system, in the south-west orientation. The floor plan of the office is shown in Fig. 1. The double skin façade had full height glazing panels (i.e. 100 % window-to-wall ratio). The glass façade technologies installed in the office space are shown schematically in Fig. 2 and the specifications summarised in Table 1. A weather station on the roof could be employed to control the façade blinds depending on the external irradiance. The façade gives access to an outdoor view of a car parking area with a low rise building and a natural green background with hills (shown in Fig. 4b in Section 2.3).

Information on the environmental services is reported in Table 2. The heating, ventilation and air conditioning (HVAC) system was composed of chilled / heated ceiling panels to provide sensible heating and cooling and a full air system for providing fresh air and controlling the humidity levels. The artificial lights were recessed ceiling-mounted lamps and always on during occupied times.

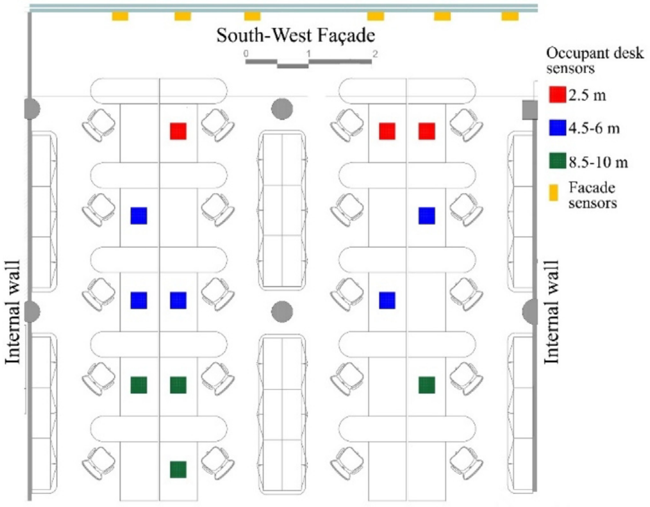

Fig. 1. Plan view of the investigated office with indication of the desks where the sensors were installed (the sensors were installed on desks located at 2.5 m (indicated in red), at 4.5–6.0 m (indicated in blue), at 8.5–10.0 m (indicated in green) and on the façade (indicated in yellow). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

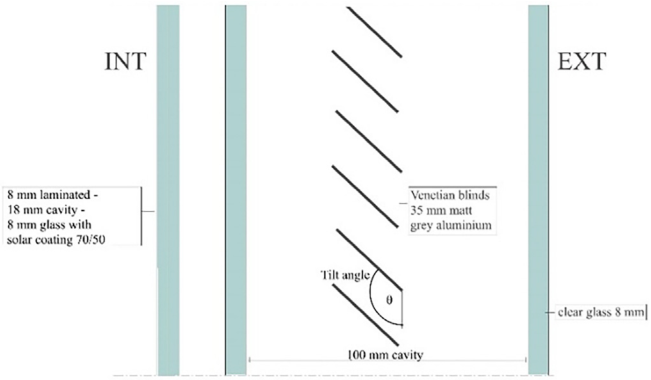

Fig. 2. Schematics showing the key features of the façades tested: double skin façade with venetian blind in the cavity. Full specifications are reported in Table 1.

Table 1
Specification of the façade tested.

Façade glazing characteristics	Façade venetian blind characteristics
DGU (8 mm glass with solar coating 70/50–18 mm cavity – 8 mm laminated) + 100 mm cavity + 8 mm clear glass	25 mm, located in the double skin facade cavity, grey matt aluminium

Table 2
Information on environmental services.

Environmental services	Control system/strategy
Lighting	Always on
HVAC	Operating time: 0700–1800 hrs Heating setpoint: 21 °C Cooling setpoint: 25 °C

2.2. Experimental design

The experiments were conducted as repeated measures from the 23rd of October 2020 to 21st of December 2020. Every day, data on indoor environmental quality and occupant feedback and interactions was collected by bespoke sensing toolkits, polling stations and questionnaires (described in Section 2.3).

During the monitoring period, occupants were exposed to two different scenarios (see Table 3). In Scenario 1, the façade blinds were controlled by an existing automated control algorithm (shown in the flowchart in Fig. 3) in which the occupants were always allowed to override the system. In Scenario 2, the automated control algorithm was disabled and the occupants could control the blind manually. Scenario 1 was repeated then in period 3 to account for any effect from the order of exposure.

The existing control algorithm aims to minimise glare discomfort, by lowering the blinds when the sun was in the field-of-view (FOV) and the radiation was above the threshold of 250 W/m^2, and tilting the slats depending on the sun elevation to block the solar beam. When the blinds were at the fully-lowered position (i.e. bottom rail at finished floor level), the automated control only changes the tilt angle depending on the FOV. When the sun is not in the field of view and the radiation is below the threshold, the slats revert back to the horizontal position to maximise outdoor view and daylight access, but the blinds are not raised (i.e. bottom rail remains at finished floor level) to preserve the operational life of the blinds and the nouse. When occupants override the system, the automated control strategy is automatically disabled 30 min.

A total of 11 occupants (4 women and 7 men; 30 % aged 31–40, 20 % greater than50, 50 % 41–50) participated voluntarily in the experimental campaign. The volunteers had no abuse of alcohol or drugs, generally healthy, advanced to proficient level of English language, and a body mass index in the range of 18–25 kg/m^2. The volunteers were recruited by email invitation from the occupants of the office space. Overall, the office space was occupied by 14 people. Occupants not participating in the data collection were asked for consent before starting the environmental and façade monitoring, while volunteers were asked for consent on both the objective and the subjective data monitoring. The study was approved by the Ethical Committee of the Department of Engineering at the University of Cambridge.

Due to the Covid-19 pandemic, the occupancy in the office space was followed a pre-defined weekly rota wherein some of the volunteers would be working from the office in a particular week and not at all in the subsequent week, e.g. a different subset of the 11 volunteers would be working form the office every week. The data collection was divided into three groups depending on the occupant distance from the façade and namely: occupants sitting at 2.5 m, occupants within 4.5–6.0 m and occupants within 8.5–10.0 m. The desktop environmental sensors were always located at the desks where the volunteers were sitting. For each volunteer, data on environmental quality, satisfaction and discomfort was collected for each scenario and during at least one week. Fig. 1.a indicates the position of the desks where volunteers were sitting during the monitoring and the location of the sensing devices, which were placed on the volunteer desks and on the façade.

Table 3
Description of the scenarios investigated in this work.

Period	Scenario Control strategy	Number of days	Dates
1	Semi-automated (allows for occupant overrides)	17	23/10–9/11
2	Manual	17	10/11–27/11
3	Semi-automated (allows for occupant overrides)	17	30/11–21/12 (from 5th to 8th of December not included)

2.3. Environmental sensing and occupant-data interfaces

A bespoke low-cost Internet-of-Things (IoT) toolkit based on the Raspberry-pi technology [15], called “BIT 2”, was developed to monitor the indoor environmental quality of the space, the façade environmental performance, occupant interaction with the façade, discomfort and environmental satisfaction. “BIT 2” is an upgraded version of the “BIT toolkit” previously described by the authors [16]. The toolkit is comprises: (i) an IoT sensing station that monitors the façade (called “BIT Façade 2” (Fig. 4a); (ii) an IoT camera-based device to monitor glare and mean radiant temperature (MRT) – (called “BIT Glare 2”, Fig. 5(a); (iii) a digital touchscreen polling station for collecting occupant feedback on discomfort (Fig. 5b) and equipped with sensors for collecting environmental data, which was located on the volunteer desk (called “BIT station 2”, (Fig. 5c); (iv) a mobile-app to collect data on satisfaction and general well-being (part of “BIT Station 2”, placed also on the volunteer desk as shown in Fig. 5a). The mobile-based web-app questionnaire was accessible through the quick response (QR) code and radio frequency identification (RFID) tags on a card, located at each desk and shown in Fig. 5.a. Details on the questions that were displayed are reported in Appendix B.

The façade toolkit (called “BIT Façade 2”) monitors the internal surface and air temperatures of the façade and the transmitted vertical illuminance. The IoT camera (called “BIT Glare 2”) monitors the vertical illuminance at the occupant eye level, since it is installed with a bracket beside the volunteer. Limitations and details of the sensing devices comprised in the toolkit are described in Appendix A.

2.4. Experimental procedure

Firstly, volunteers were asked to answer a general anonymous survey to collect information on their demographic data (e.g. age, gender etc.) and their general satisfaction with the office. At the end of this first questionnaire, they received an identification code, which they subsequently used to log into the polling station (BIT Station 2) and into the mobile app. Volunteers were asked to perform their daily tasks as normal and to complete the mobile-app questionnaire at least every-two hours. They were also invited to express their discomfort at any time by pressing one of the coloured-coded buttons on the touchscreen in Fig. 5.b. The volunteers were also instructed to interact and override with the façade as normal and report the reason for their interaction in the mobile-app. Volunteers could interact and override the blinds in the office through a touchscreen-based controller, located in proximity of their desks (shown in Fig. 6).

Before the monitoring scenarios stages, the researchers had periodic meetings with the volunteers to explain the aims of the measurement campaign and to demonstrate the interfaces for occupant feedback. During the two weeks prior to the official start of the monitoring, volunteers were asked to use and test the interfaces and familiarise with them. The data collected in this preliminary familiarisation phase was not considered in the final post-processing. Details on the statistical analysis are reported in Appendix C.

The total number of “discomfort events” are the sum total of times volunteers pressed the corresponding colour-coded button. The difference in the number of discomfort events was used to compare the scenarios. The number of volunteer interactions with the blinds were also considered by summing up the number of interactions per day and considering the reason reported by the volunteers for interacting with the blinds.

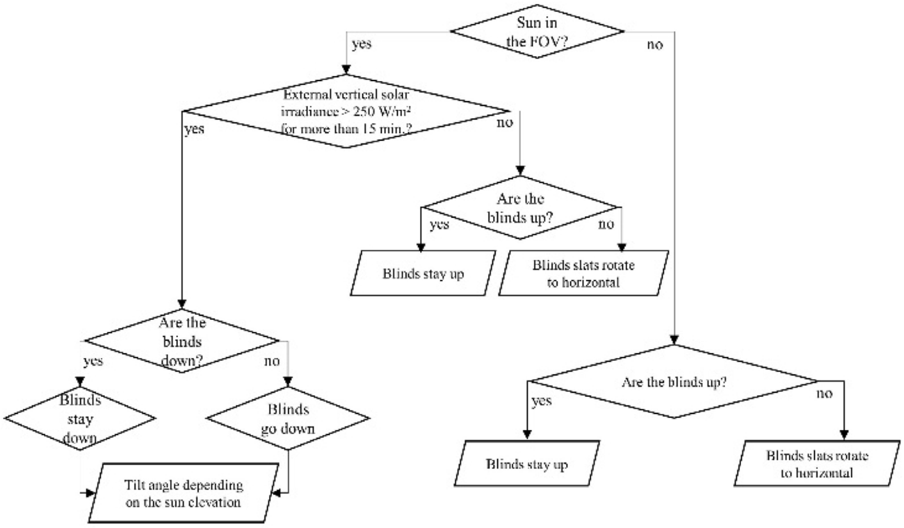

Fig. 3. Control algorithm for the blind control strategy. For the whole monitoring period, the blinds stayed always down and only the angle of tilting was changing.

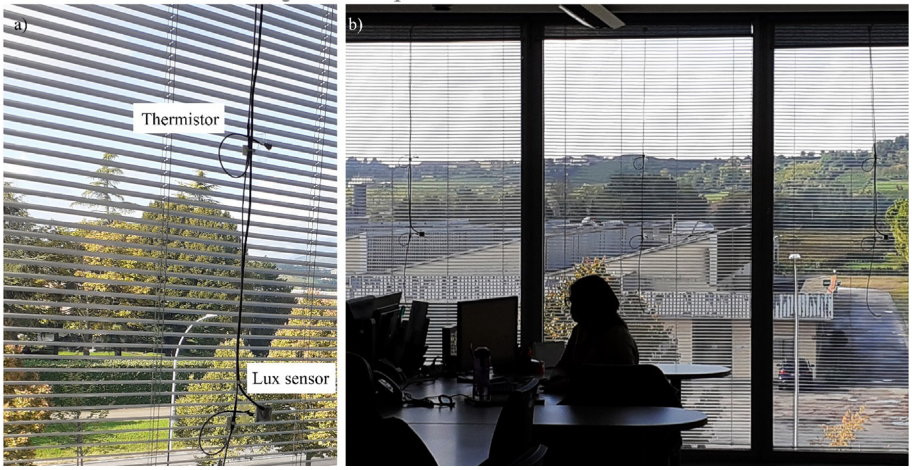

Fig. 4. a) View of the façade with the sensing toolkit installed ("bit façade 2"); b) view of three out of the six façade bays under monitoring.

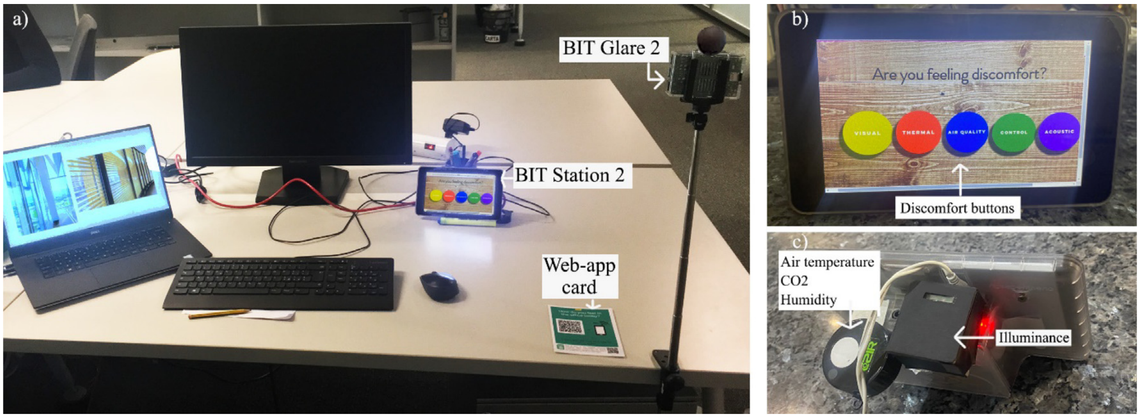

Fig. 5. a) view of the occupant desk with the "bit 2 station", the "bit glare 2" and the web-app card; b) front view of the touchscreen with the digital colour-coded discomfort buttons; c) back view of "bit station 2" with the illuminance sensor and the co_2, air temperature and humidity sensors.

Fig. 6. View of the touchscreen-based controller used by occupants to change the height and the tilt angle of the blinds.

3. Results

3.1. Occupant-façade interaction

Fig. 7 shows the average level of occlusion of the whole façade during the scenarios 1, 2 and 3, while Fig. 8.a shows the total number of occupant overrides for scenario per reason of interaction. The average level of occlusion was computed by considering the arithmetic mean of the occlusion level of each façade bay. Before the monitoring started, the façade was exclusively manually operated by occupants because no automated control had been implemented yet. At the start of the monitoring, volunteers were asked to express via web-based questionnaire to recall or estimate how frequently they interacted with the façade. Fig. 8.b shows the result of the questionnaire. Most occupants stated that they interact infrequently with the façade and this response was also confirmed by the data collected on occupant-façade interaction during the monitoring period. As shown in Fig. 7, across all the scenarios occupants only interacted with the blinds on an average of 2 to 3 times per day.

During all the scenarios, occupants never fully-raised the blinds and they only interacted with the blinds to change the tilt angle of the blind slat. The manually operated scenario (scenario 2) registered the largest number of interactions. Period 3 registered a lower number of interactions than in the first period, despite the façade technology and the automated control strategy were identical. This difference was due to the lower levels of solar radiation in the third period, which were often below the threshold of activation for the automated control and, therefore, occupant did not have to interact with the façade to restore the daylight / view access. In the scenario 2, the main driver of occupant interaction with blinds was the desire of mitigating discomfort from glare.

Table 4 shows the total amount of time when the façade was either fully occluded (occlusion level = 100, where all the façade bays have fully closed blind slat and, therefore, a tilt angle equal to 180°), or with a very low level of occlusion (occlusion level <30, where all or nearly all the blind slats were horizontal and, therefore, with a tilt angle equal to 90°) or at intermediate occlusion levels. During the semi-automated scenarios (period 1 and 3), the blinds were fully lowered and closed for a longer amount of time than during the manual scenario. However, the blinds were also left fully open (horizontal slat position, tilt angle equal to 90°) for a similar amount of time to the manual scenario, while in the manual scenario blind slats were often left at intermediate angles. In this case study, the manual control scenario was effective in achieving high levels of daylight, because in several occasions, occupants fully opened the blinds at their arrival in the morning to maximise view and daylight access and did not interact with the blinds afterwards.

In this study, the main difference between the automated and the manual controls was the time of response. The automated controls were able to anticipate glare or overheating by monitoring the incident solar radiation on the façade and the position of the sun, thereby closing the blinds before occupants would have felt in discomfort. Conversely, in the manually controlled scenario, only when occupants had already experienced glare, they would interact with the blinds to restore their comfort, thereby blocking the

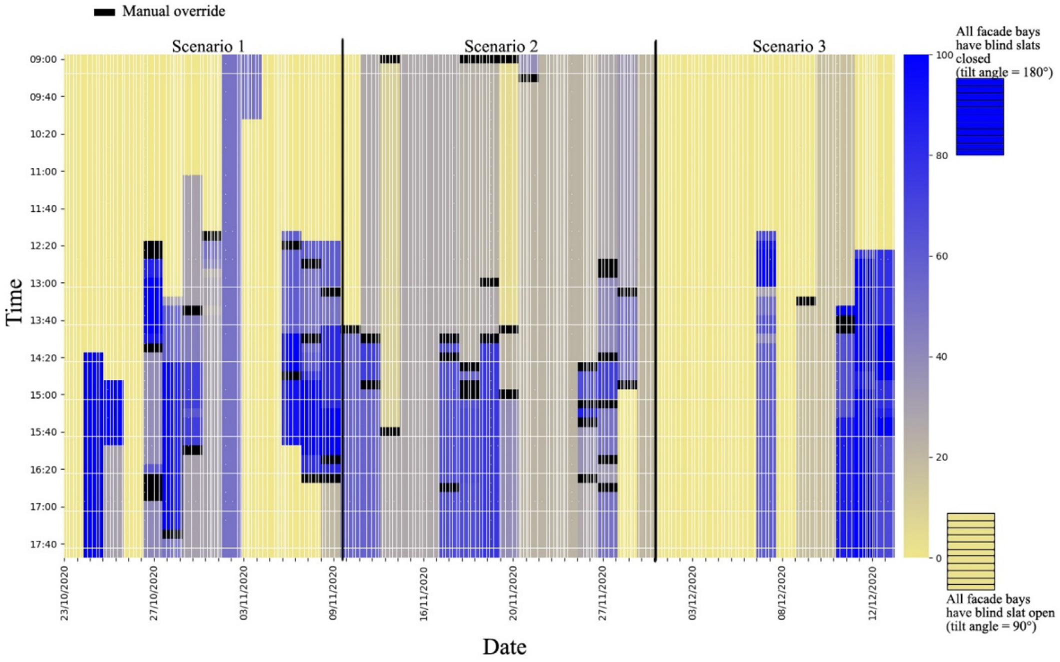

Fig. 7. Average occlusion level of the façade, from 0 (slats are at the horizontal position) to 100 (slats are fully closed): a) period 1 (automated), period 2 (manual control), period 3 (automated).

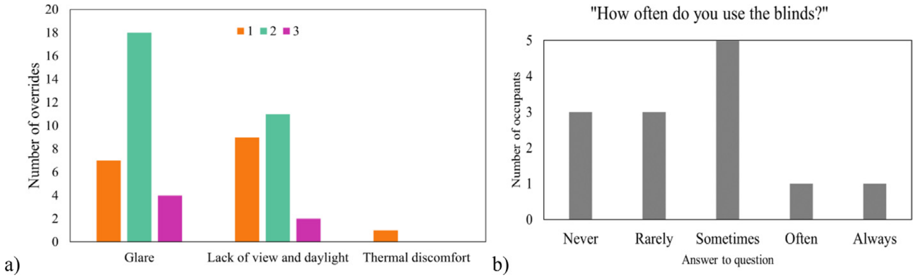

Fig. 8. a) Reason given for overriding in the periods 1, 2 and 3; b) volunteers' response to the question "how often do you use the blinds?".

Table 4
Number of hours with unobstructed view for each scenario.

Scenario	Number of hours with blinds fully open	Total number of hours	Percentage of hours with blinds fully open
Period 1 – Semi-automated	105	167	62 %
Period 2 – Manual	4	156	3 %
Period 3 – Semi-automated	90	145	62 %

incoming solar radiation. This delay in the response to glare and oversupply of solar radiation had detrimental effects on the thermal and visual quality of the environment, as discussed in the next section.

3.2. Objective assessment

3.2.1. Façade performance

The average daylight illuminance transmitted through the whole façade is shown in Fig. 9. The average daylight illuminance was computed as the arithmetic mean of the daylight transmitted through each of the façade bays. The transmitted illuminance was measured at the centre of pane of each façade bay. Continuous measurements over one minute were taken at 10 min intervals and averaged over the corresponding minute. Despite similar levels of external solar radiation, scenario 2 had higher levels of transmitted illuminance than the scenario 1 and, mainly, during the peak hours (12:00–15:00 hrs), as also shown in Fig. 10.a. As mentioned previously in section 3.2, the manually controlled scenario was less effective in mitigating excessive levels of solar radiation. The higher levels of solar radiation influenced the surface temperature of the glazing, which on average was higher in the scenario 2 than in scenario 1 (Fig. 10.b).

A similar trend is observed in the average surface temperature of the façade inner glazing, which reached temperatures above 35 °C ± 0.5 °C in several occasions (see Fig. 10.b). Despite lower levels of external solar radiation, during the third period of measurements the values of transmitted illuminance were higher (see Fig. 10.a) because of the lower elevation of the sun in December with respect to end of October. Surface temperatures of the inner glazing in period 1 and 3 (semi-automated) were found to be similar because the external temperature was lower and compensated the larger amount of absorbed solar radiation by the glazing in the scenario 3 (see Fig. 10.b).

3.2.2. Thermal quality and indoor air quality

Despite similar levels of solar radiation, scenario 2, where the façade was only manually controlled, showed higher peaks in operative temperature, as shown in Fig. 11. This was evidently true for the locations closer to the façade (Fig. 11a). When the sun was in the field of view (from 12:00 to 16:30 hrs), the average operative temperature was also much higher in the scenario 2 than in the semi-automated scenario, since the blinds were often left fully raised by the occupants and therefore there no effective mitigation of the solar gains and overheating. This was also confirmed by the supply temperature of the cooling system that differ across the three periods only after 3 pm, when instead the indoor temperatures were very similar across the three periods. Therefore, solar gains were not compensated by the cooling and period 2 presented higher levels of operative temperature. The third period was characterised by low levels of external solar radiation and air temper-

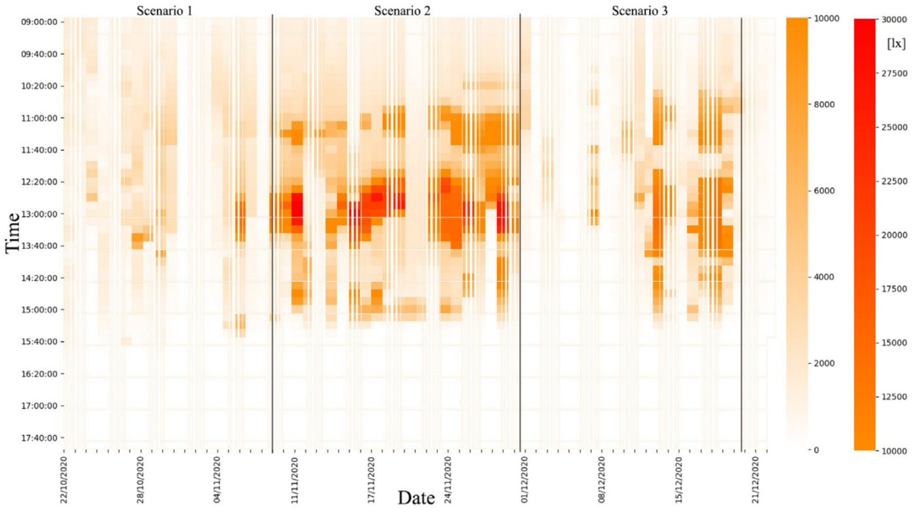

Fig. 9. Average daylight illuminance transmitted through the façade during the scenario 1, 2 and 3.

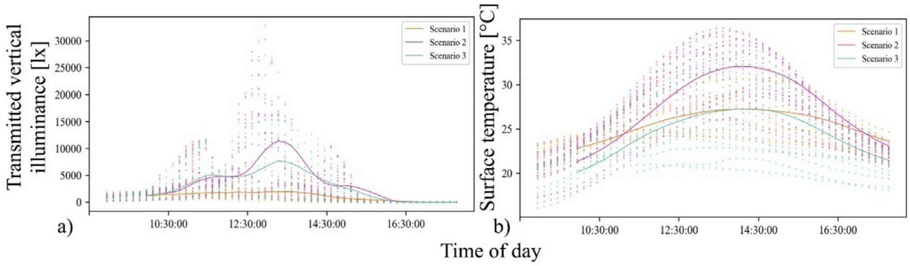

Fig. 10. a) Average and total transmitted daylight vertical illuminance through the façade per time of the day; b) average and surface temperature of the inner glazing of the façade in the period 1, 2 and 3 per time of day.

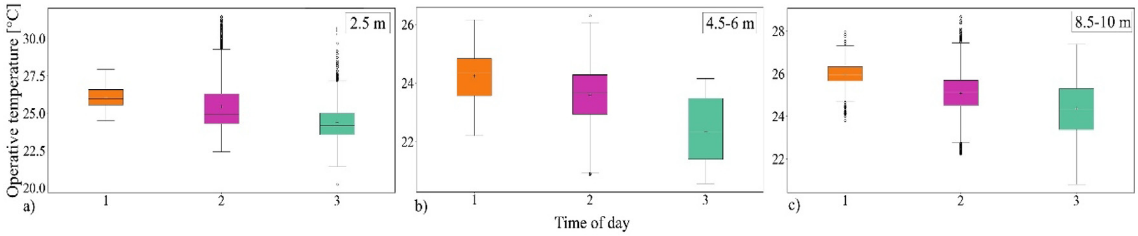

Fig. 11. Distribution of operative temperatures throughout the scenarios: a) at 2.5 m distance from the façade; b) at 4.5–6 m from the façade; c) at 8.5–10 m from the façade. In the plot, the rectangle represents the second and third quartiles of the data distribution, the vertical line shows the lower and upper quartile, the data points represent the outliers, the cross represents the average and the horizontal line the median.

ature, which induced a generally lower distribution of indoor operative temperatures in comparison to other scenarios. Table 5 shows also the number of hours with operative temperatures higher than 27°, which also confirms the semi-automated scenario was more effective in maintaining comfortable levels of operative temperature (see Fig. 12).

The levels of CO_2 were similar across the scenarios. This was expected, because the control of the façade does not have any direct effect on the air quality and air changes. The location further from the façade (Fig. 13c) had lower levels of CO_2 because this area of the office had a lower occupancy than closer to the façade. Nevertheless, the values recorded were within adequate limits for indoor environmental quality.

3.2.3. Visual quality

Occupant desks were located at a relatively large distance from the façade. The closest occupant desk was located at 2.5 m from the façade. For this reason, the levels of daylight were generally low throughout the scenarios and especially at further distance from the façade (4.5–6 m and within 8.5–10.0 m from the façade), as shown in Fig. 14. The contribution of the artificial lights was also poor since on several occasions, the horizontal illuminance on the desk was below 300 lx (see Table 6). The highest daylight levels were recorded for the scenario 2, where the blinds were often left fully open by the occupants during the peak hours (see Table 6, the generally lower level of façade occlusion within 12:00 and 16:00 hrs for scenario 2 in Fig. 7, and higher level of transmitted illuminance in Fig. 9 within the same time range). Because of the higher levels of transmitted daylight illuminance, excessive levels of vertical illuminance at the occupant eye level were often recorded in the scenario 2, as shown in the outliers in Fig. 15 that were often above 2000 lx. The vertical illuminance at the occupant eye level was on average higher for period 2 than in the other scenarios and, in particularly, when the sun was in the field of view (from 12:00 to 16:00 hrs), as shown in Fig. 16. This was very evident at the positions closest to the façade (2.5 m), but also significant at the locations further from the façade (4.5–6.0 m and 8.5–10.0 from the façade), due to the low sun elevation and the related large sun beam penetration depth. The vertical illuminance was on average higher for period 3 than in period 1, this is due to a relatively lower sun elevation in scenario 1.

Table 5
Number of hours with operative temperature higher than 27° at the location of 2.5 m, 4.5–6 m and 8.5–10 m from the façade.

Scenario	2.5 m	4.5–6 m	8.5–10 m
Period 1- Semi-automated	12	1	6
Period 2 – Manual	73	5	11
Period 3 – Semi-automated	19	0	1

3.3. Subjective assessment

3.3.1. Discomfort events

The total number of discomfort events per domain and distance form the façade are shown in Fig. 17. In addition, Fig. 18 shows the reason indicated by occupants for perceiving discomfort. This represents the number of times the corresponding colour-coded domain button were pressed. Overall, scenario 1 recorded the highest number of discomfort events. However, this was often due to the environmental building services, as shown in for the thermal discomfort, where occupants were often feeling cold because of the HVAC system and, in particular, at the position further from the façade, where the solar gains were perceived less. During the scenario 1, no occupant expressed thermal discomfort because of the solar radiation, but they did report feeling uncomfortably warm. For the visual discomfort, in the scenario 2 occupants reported the highest number of events of glare discomfort, which is also confirmed by the highest number of interactions with the blinds performed by occupants to mitigate glare, as reported in Fig. 8.a. Occupants often reported discomfort with the outdoor view access and daylight during the period 1 and 3, although the total amount of time when blinds were fully raised was similar throughout all the scenarios. In the period 1 and 3 (semi-automated scenarios), discomfort with glare, lack of view and level

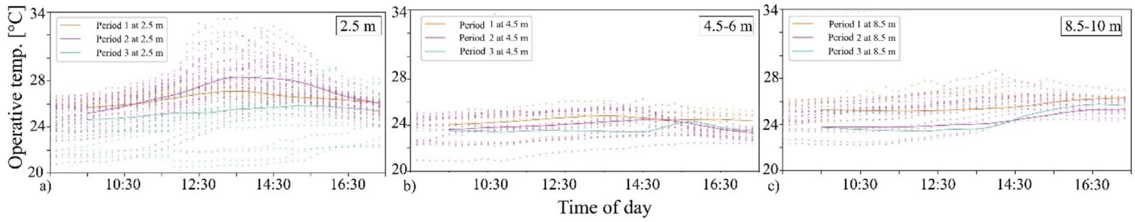

Fig. 12. Distribution and average operative temperature throughout the day and per scenarios: a) at 2.5 me from the façade; b) at 4.5–6 m from the façade; c) at 8.5–10 m from the façade.

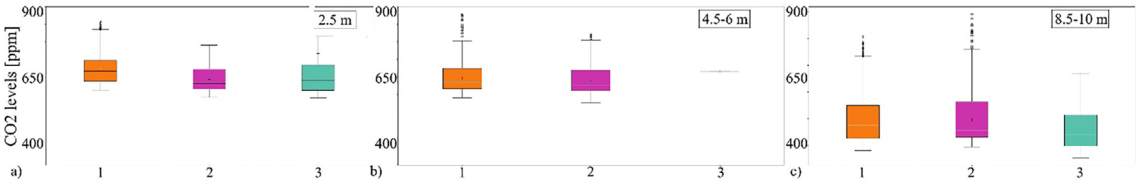

Fig. 13. Distribution of CO_2 levels throughout the scenarios and at three distances from the façade: a) 2.5 m from the façade; b) 4.5–6 m from the façade; c) 8.5–10 m from the façade.

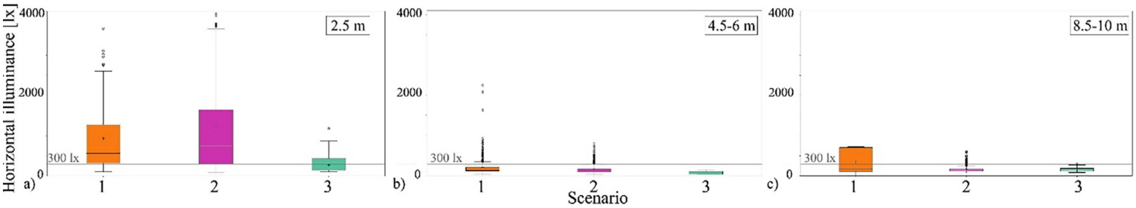

Fig. 14. Distribution of horizontal illuminance on the desk of the occupants: a) position close to the façade (2.5 m); b) desks located within 4.5 and 6.0 m from the façades; c) desks located within 8.5–10.0 m from the façade.

Table 6
Number of hours with horizontal illuminance below 300 lx, between 300 lx and 2000 lx and above 2000 lx at the location of 2.5 m from the façade.

Scenario	Number of hours with horizontal illuminance lower than 300 lx	Number of hours with horizontal illuminance between 300 lx and 2000 lx	Number of hours with horizontal illuminance higher than 2000 lx
Period 1- Semi-automated	24 %	67 %	9 %
Period 2 – Manual	20 %	54 %	26 %
Period 3 – Semi-automated	33 %	66 %	0

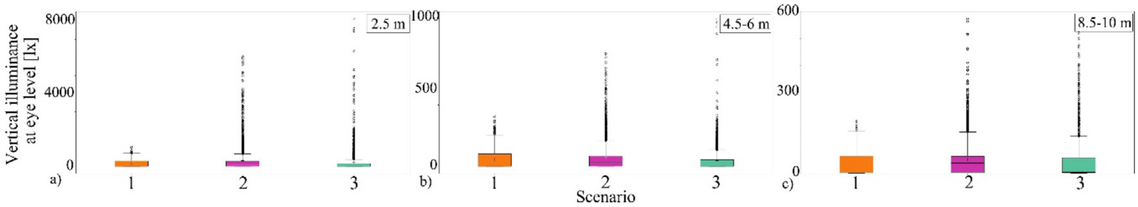

Fig. 15. Vertical illuminance at the eye level of the occupant at different distances from the façade and per scenario: a) position close to the façade (2.5 m); b) desks located within 4.5 and 6.0 m from the façades; c) desks located within 8.5–10.0 m from the façade.

of daylight were especially encountered by the occupants sitting furthest from the façade (8.5–10.0 m).

Glare discomfort events were almost always associated with blinds being mainly open (only in two occasions blinds were already closed). Daylight and view discomfort events were mainly associated with blinds being down, but several times (70 % of the time blinds were mainly closed, but for 30 % of the time blidsn were already open). This was due to the fact it was either overcast or the users were sitting very far from the façade (8.5–10 m). Acoustic discomfort was found to be associated to blind movement only once. Thermal discomfort for high temperature was always associated to blinds open, instead discomfort for lower temperatures was not related to blind position.

Discomfort with the level of personal control was perceived by volunteers in relation to both the environmental services (HVAC and artificial lighting), and the façade. Discomfort with the control

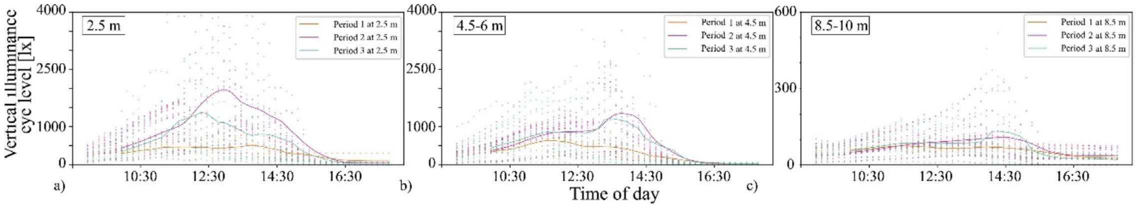

Fig. 16. Distribution and average vertical illuminance at the eye level of the occupant at three different distances from the façade and per period: a) position close to the façade (2.5 m); b) desks located within 4.5 and 6.0 m from the façades; c) desks located within 8.5–10.0 m from the façade.

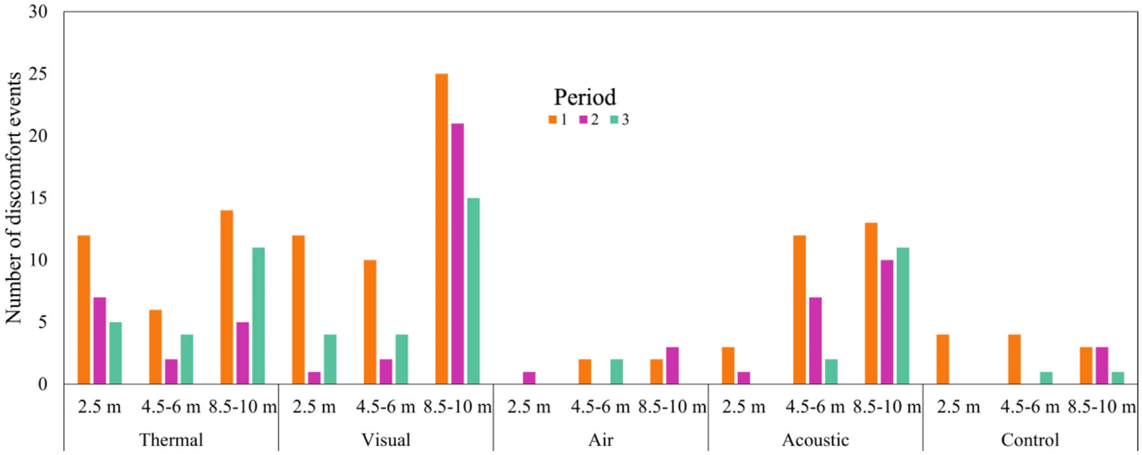

Fig. 17. Total number of discomfort events per scenario, comfort domain and distance from the façade.

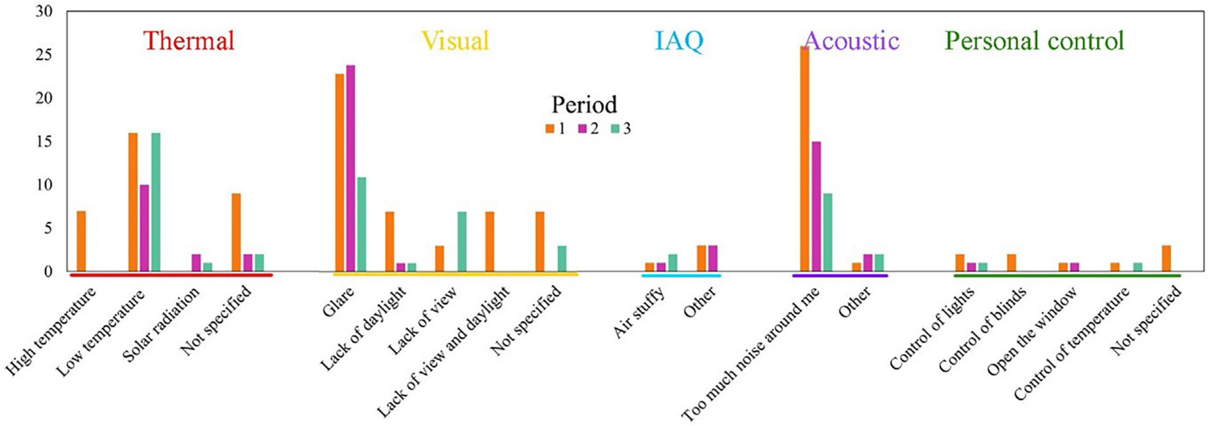

Fig. 18. Total number of discomfort events per domain and reason of discomfort.

of the façade was reported by occupants because they could not open the window (the façade had not openable vents), and they perceived low personal control of the blinds when sitting at desks located far from the façade (8.5–10.0 m). Acoustic discomfort was mainly due to the background noise in the open space office, which was especially perceived at the location furthest from the façade, which were located closer to the core of the office and coffee breaks room.

3.3.2. Level of environmental satisfaction

Despite the first period recorded the highest number of discomfort events, occupant satisfaction with the indoor environment was generally higher during the semi-automated scenario (period 1 and 3) than in the manual scenario (period 2). Differences with the level of environmental satisfaction varied depending on the distance from the façade and throughout the day. The differences between the scenarios were larger during peak hours, when the sun was in the field of view and the incident radiation was the highest. The level of habituation, workload, happiness, enjoyment of the task and fitness and rest did not vary significantly across the scenarios, therefore they were not included in the final linear mixed model. The outdoor temperature resulted not significant for the environmental satisfaction on all the domains.

Thermal satisfaction (shown in Fig. 19.a) was significantly lower in the manual scenario than in the semi-automated at the locations closest to the façade (2.5 m), since in the manually controlled scenario the temperatures were higher due excessive solar gains. At further distances, the difference was not significant but still very large.

Satisfaction with the level of personal control (shown in Fig. 19.b) was significantly higher in the scenarios that combined automated control with manual one (period 1 and 3). Satisfaction with

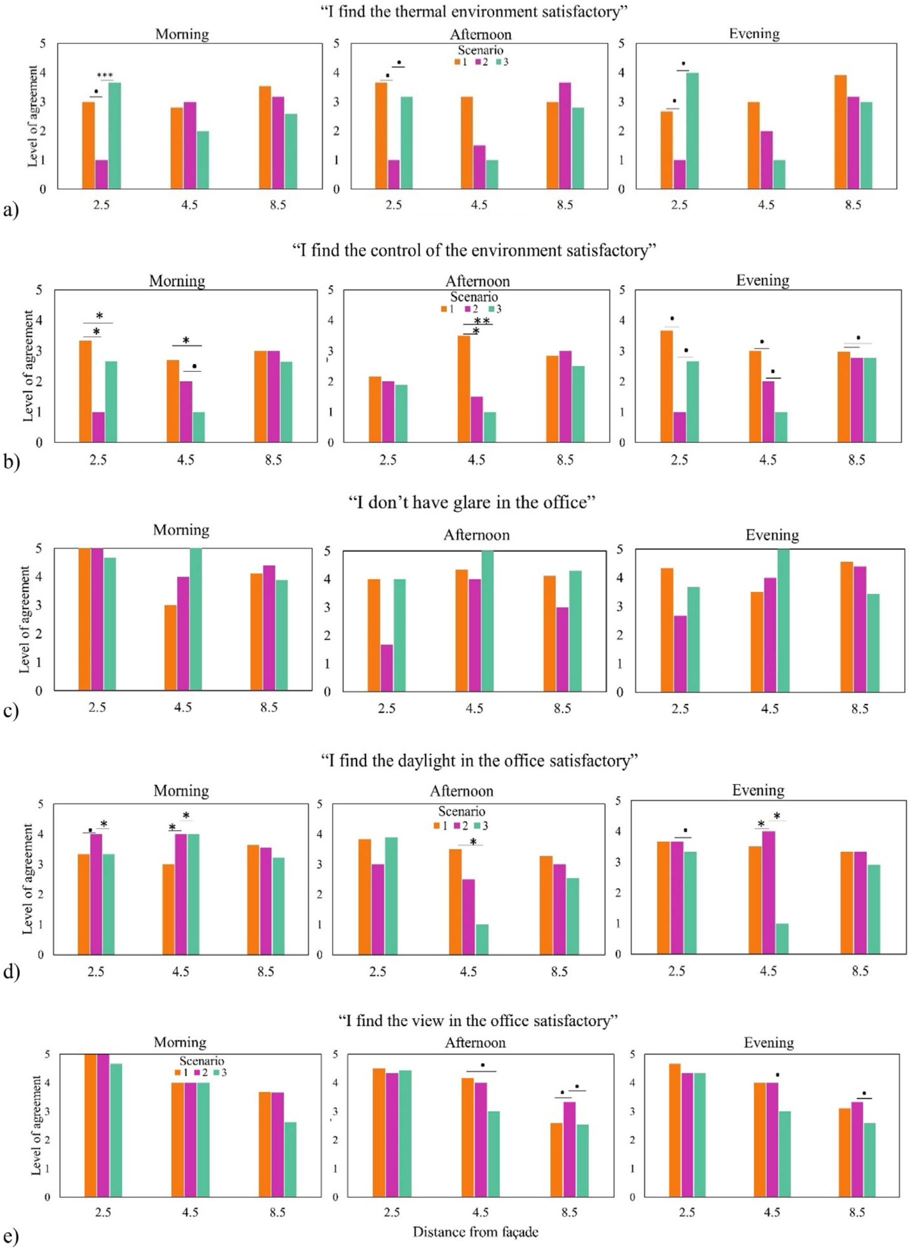

Fig. 19. Average level of agreement with the statement given at the top of each chart at different distances from the façade (2.5, 4.5–6.0 m, 8.5–10.0 m) and at three different time of the day: morning (from 09:00 to 12:00), afternoon (from 12:00 to 15:00) and evening (from 15:00 to 18:00). The level of significance of the difference between scenarios is reported as asterisks or dots depending on the p-value: when the p-value is lower than 0.1, a dot is reported (.); when the p-value is lower than 0.05, one asterisk (*); when the p-value is lower than 0.01, two asterisks are reported (**); when the p-value is lower than 0.005, three asterisks are reported (***).

the level of personal control could have been affected by the satisfaction with thermal environment and the daylight, which were found to be significantly correlated with the satisfaction with the level of personal control.

The satisfaction with glare mitigation (shown in Fig. 19.c) was higher in the automated scenarios than in the manually controlled scenario. This was expected since the automated control strategy was effective in preventing glare by closing the blinds when the sun was in the field of view (as shown in Fig. 7 and Fig. 9), avoiding excessive daylight and vertical illuminance at the occupant eye level. Conversely, in the manual scenario occupants would wait to experience glare before closing the blinds.

Satisfaction with the level of daylight (shown in Fig. 19.d) was significantly higher in the morning and in the evening for scenario 2 than in scenario 1, but lower during the afternoon when the façade had the sun in the field of view. A similar trend was shown in the satisfaction with outdoor view access, as shown in Fig. 19.e).

The level of acoustic satisfaction did not show any significant difference across the scenarios and the time of the day and, therefore, results are reported as daily averages in Fig. 20.a. Differences in acoustic satisfaction were not expected between the scenarios, since they had the same façade technology. However, the desk locations further from the façade were the closest one to the corridor and office coffee break rooms and, therefore, occupants sitting in these locations reported lower levels of acoustic satisfaction than closer to the façade.

Non-significant differences were found with the contentment with the office space or the perceived productivity, while the perceived ease of concentration (shown in Fig. 20.b) was higher in the automated control scenario (period 1 and 3). One of the reasons for

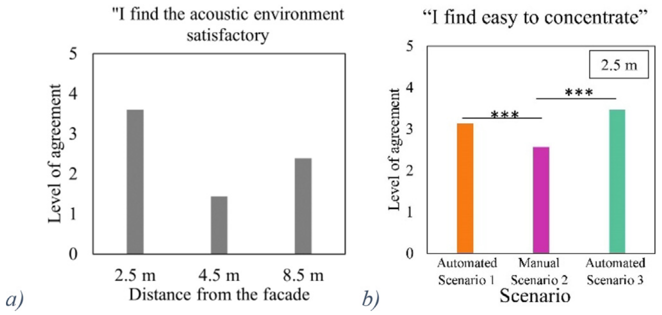

Fig. 20. a) Average level of agreement with the statement given above the plot ("i find the acoustic environment satisfactory) per distance from the façade; b) average level of agreement with the statement given above the plot ("i find easy to concentrate"). the level of significance of the difference between scenarios is reported as asterisks or dots depending on the p-value: when the p-value is lower than 0.1, a dot is reported (.); when the p-value is lower than 0.05, one asterisk (*); when the p-value is lower than 0.01, two asterisks are reported (**); when the p-value is lower than 0.005, three asterisks are reported (***).

this could be the lower number of occupant interactions in the semi-automated scenario than in the manual scenario.

3.3.3. Overall level of occupant satisfaction

Fig. 21 compares the average levels of occupant satisfaction during the day and across the environmental domains. In these radar diagrams, each environmental domain has an equal weighting, although the hierarchy of importance of each environmental domain is expected to be highly individual and to vary across occupants. At distances closer to the façade (2.5 m), the area enclosed by the graph is significantly larger for the automated scenarios with manual override than for the exclusively manually-controlled one, implying an overall larger satisfaction of occupants with the environment. This trend was also confirmed in the evening for the group located at 2.5 m (see Fig. 24 in Appendix C). At larger distances from the façade, overall differences across the scenarios are less noticeable, since the façade has a lower impact. If we compare period 1 and 2, which had similar external conditions, the semi-automated scenario yields overall higher satisfaction levels at 4.5–6.0 m from the façade, while at the furthest distances (8.5–10.0 m) from the façade the overall levels of satisfaction were very similar. In the morning and in the evening, differences between the surface area of graphs were negligible for distances larger than 4.5 m from the façade, confirming that the influence of a façade depends on the time of the day and, therefore, monitoring data should be collected throughout the day [5]. The results for the morning and evening periods are reported in Appendix C.

At the end of scenarios 1 and 3, occupants were also asked to provide feedback on the automation system through web questionnaires. Fig. 22 shows the distribution of occupant level of agreement with the statements reported above the plot. Occupants were asked to express their agreement by selecting a number from 1 (strongly disagree) to 5 (strongly agree). The average satisfaction with automation system of the façade was slightly lower the median agreement value and, therefore, improvements of the automated control could be beneficial. Overall, volunteers were equally split between finding disruptive the automation system and not finding it disruptive, therefore these results are not conclusive to understand the disruptiveness of automated blinds. Occupants were more satisfied when the automated control was operating the blinds to raise or open them, rather than when closing the blinds. This was aligned with the overall dissatisfaction of occupants with the daylight and outdoor view access. However, the reaction time (i.e. the time that elapses between when occupants perceive a discomfort condition and when the façade responds to mitigate that discomfort or to restore daylight) was also reported as unsatisfactory by questionnaires responses. In all cases the volunteers would have preferred the control system to react more quickly in several occasions.

4. Discussion

The average façade occlusion was similar between the scenarios, occupants in the office under investigation showed to be actively controlling the blind to improve their access to the outdoor view and daylight. Conversely to these results, previous work [16] had shown that manually controlled façade provided lower daylight access than automated façades, since occupant tended to operate blinds only occasionally, thereby missing several opportunities for daylight harvesting or access to outdoor view. However, the large number of contextual factors that influence occupant behaviour in buildings [17], the differences in occupant individual preferences on interaction strategies, such as different patterns of behaviour between "active" and "passive" users in buildings [18], and indoor environmental quality, make difficult to generalise findings from one case study. The influence of a control strategy or a façade typology showed to vary depending on the local occupant expectations and background or other contextual factors such as façade typology, control strategy and interface design [4]. For instance, daylight access was generally low in the office, given that occupants were sitting at least 2.5 m apart from the façade and up to 10.0 m from it. The poor visual environment could have triggered a larger number of occupant interaction with the blinds to restore daylight.

Despite occupants were on average able to effectively interact with the blinds to restore daylight and outdoor view access during the manually controlled scenario, this scenario was less efficient than the automated ones in preventing oversupply of daylight or undesirable solar gains. Blinds were closed by occupants only

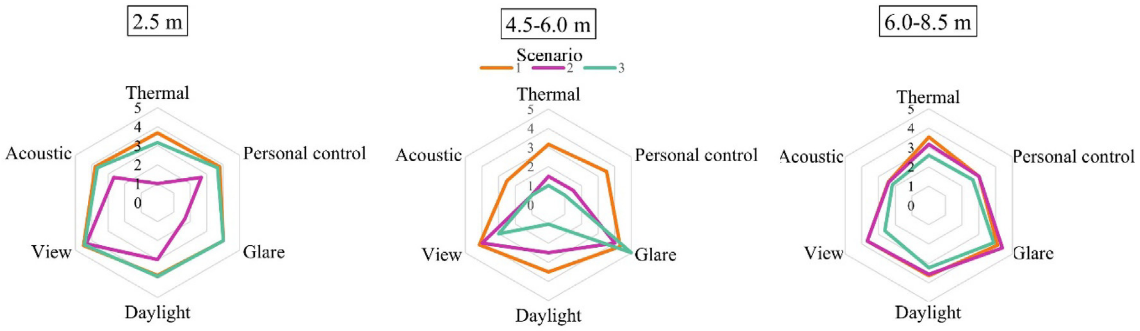

Fig. 21. Overall environmental satisfaction in the afternoon (12:00–15:00 hrs) and at different distances from the façade.

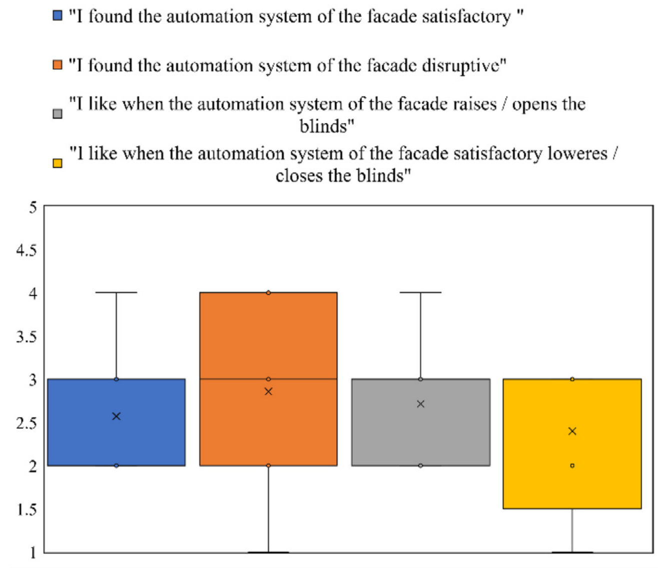

Fig. 22. Level of agreement with the statements given above the plot. In the plot, the rectangle represents the second and third quartiles of the data distribution, the vertical line shows the lower and upper quartile, the data points represent the outliers, the cross represents the average and the horizontal line the median.

towards the end of the peak hours (12:00–15:00 hrs), when they would have already felt uncomfortable with the visual or thermal environment. Therefore, the manually controlled scenario was less effective in reducing undesirable solar heat gains and daylight levels, as shown by the much higher levels of illuminance transmitted by the façade, operative temperature, and vertical illuminance at the eye level at the occupant locations and, in particular, for those sitting closer to the façade (2.5 m). This is the reason why, in the scenario 2, occupants reported the highest number of glare discomfort events, which was also confirmed by the highest number of blind interactions aiming at mitigating glare, as shown in Fig. 8. Therefore, the results herein presented showed the automated control of façade has the potential to enhance occupant satisfaction, but satisfactory levels of occupant-façade interaction require bespoke design solutions because of the existing differences between individual occupant preferences and contextual conditions in buildings. For instance, the interaction strategy and the automated control system of the façade investigated in this work recorded a higher number of discomfort events than the manually controlled scenario for outdoor view and daylight access, which could have been prevented.

Since the external conditions of the first and second scenario were slightly different, the effect of the order of exposure on occupant discomfort and satisfaction is not clear. Nevertheless, few trends seemed confirmed regardless of the order of exposure: a higher tendency of feeling uncomfortable with the lack of view and daylight in the period 1 and 3 with respect to the scenario 2; higher glare discomfort in the scenario 2 with respect to semi-automated scenarios and, vice versa, a higher satisfaction with glare mitigation in the scenarios 1 and 3; higher thermal satisfaction in the scenarios 1 and 3 than in the scenario 2; a higher satisfaction with the level of personal control in the scenarios that combined automated and manual control, as shown by previous work of Stevens [9], where a higher satisfaction with perceived control was correlated with a higher perceived reliability of the automated control system.

Although volunteers did not perceive the automated control as disruptive and the overall environmental satisfaction was higher than in the manual scenario, as shown in Fig. 21, occupant satisfaction with the automated strategy could have been higher than reported, as shown in Fig. 22. The control system was not perceived as disruptive, given the very low noise produced by the façade during its operation and by the relatively large distance between occupants and the façade. However, the lack of access to outdoor view and daylight influenced occupant satisfaction with the automated control. The control strategy followed a too conservative approach, by closing the blinds whenever the sun was in the field of view. Occupants reported also to be dissatisfied with the time of reaction of the control system. The current system would wait 15 min before performing a control action to avoid high frequency blind movements due to variable sky conditions. This delay in response was found to be unsatisfactory by occupants. Therefore, a more occupant-centred strategies that can effectively understand when closing the blinds, thereby promptly actuating the blinds and in the timeliest manner, would be beneficial for occupant satisfaction, avoiding unnecessary blind deployment and maximising access to daylight and outdoor view. In this sense, further work is required in linking occupants to the automated controls, seamlessly closing the feedback loop between occupants and automated controls. Further work on automated control's reaction times and speed of reaction would be beneficial.

The self-reported ease of concentration was significantly much higher in the semi-automated scenarios than in manual scenario, however still not very high (the level of agreement was 3 out 5). Although this work did not investigate in detail the effect of façade controls on occupant concentration, a better interaction strategy between occupants and automated controls could also improve occupant perceived concentration in the office space.

5. Conclusion

This work monitored indoor environmental quality, occupant satisfaction, interaction and discomfort in a real office space. Occupants were exposed to two different control scenarios: a scenario where the façade was automatically controlled and occupants could override the control actions, and a scenario where the façade was only manually controlled by occupants. Occupants were exposed twice to the same automated control strategy, before and after experiencing the manually controlled façade, to assess whether the order of exposure had any effect on the overall response of the users. The results herein presented have some limitations that constrain their applicability and generalisation, such as some differences in external weather conditions between the scenarios and a low number of volunteers (11 people). The experiments were performed in a specific geographical location and, therefore, further work is required to extend these results to other climatic contexts. Nevertheless, this work provides new knowledge on occupant satisfaction and interaction with semi-automated dynamic façades by describing the integrated multi-domain response of occupants to different control strategies of the façade.

As shown by previous work [5,16], the influence of the façade varies throughout the day, being larger when the sun is in the field of view, and across the floor plan, being the highest at shorter distances from the façade. Monitoring the influence of the façade at several locations and at several time of the day is therefore confirmed to be pivotal to fully capture the influence of façades on the indoor environment and on occupant interaction, satisfaction and discomfort. An integrated multi-domain approach showed to be necessary when capturing the influence of the façade on occupant satisfaction and interaction. By only focusing on one environmental domain or aspect of occupant satisfaction, the integrated influence of contextual conditions, satisfaction with more than one domain and personal control, and of individual preferences would have led to a partial understanding of the overall satisfaction with the indoor environment and the façade. For instance, despite satisfaction with access to an outdoor view is pivotal for occupant acceptance and overall satisfaction, in this case study, the satisfaction with the thermal environment and the glare mitigation played a significant role in defining the success of the automated control strategy *versus* the manually controlled one. In addition, the overall occupant satisfaction with the automated strategy could have been higher, but only by adopting an integrated multi-domain approach was possible to identify the potential areas of improvements (e.g. time of reaction and daylight access).

Data availability

Data will be made available on request.

Declaration of Competing Interest

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

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Appendix A. Details and limitations of the sensing toolkit BIT 2

Since BIT glare uses the vertical illuminance to self-calibrate the images, this low-cost device can underestimate the luminance levels and the presence of glare and, therefore, for this study, results are discussed only in terms of vertical illuminance at the eye level. In addition, a small globe temperature sensor (5 cm radius) was installed on the top of the camera to monitor the mean radiant temperature (MRT). The front of "BIT station 2" has a touchscreen interface where occupant can record the presence of visual, thermal, air quality, acoustic or personal control discomfort by pressing the corresponding colour-coded button. The back side of "BIT station 2" has an illuminance sensor and CO_2, air temperature and humidity sensors. Details on the sensing devices and their accuracy are reported in Table 7.

In the mobile-app questionnaire, volunteers were asked to express their level of agreement with several statements on the environmental satisfaction, their satisfaction with the office space, the level of personal control, their self-perceived productivity and ease of concentration. The level of agreement is reported by selecting one value from a scale of one to five, where one corresponds to "strongly disagree" and five to "strongly agree". Statements on perceived happiness, level of workload, rest, fitness level, enjoyment with the task being performed, were also included in the mobile-app questionnaire to monitor other potential factors that could influence occupant response. The statements are listed in Appendix B.

The data from the low-cost sensing stations was automatically stored and displayed on a cloud-based storage on the InfluxDB platform [19]. This allowed to automatically process the data and visualise it in real time on bespoke dashboards. Data on the HVAC was monitored by the building management system (BMS). In addition, data was also collected by a weather station on the roof of the building, which was also used to control the façade. The automated control system logged also the position and tilt angle of the blinds, and the user overrides of the blinds.

The data collection procedure can benefit by also adding camera monitoring of the blind positions in addition to tracking the blind control state.

Table 7
Description of the characteristics of the sensing devices included in "BIT 2".

Toolkit name	Sensing device	Characteristics
BIT Façade 2	Thermistors	DS18B20 [20] Accuracy: ± 0.5 °C Range: −55 °C to +125 °C Resolution: ± 0.1 °C
	Illuminance sensor	OPT3001 [21] Includes optical filter to match human eye response Range:0.01–83 k lx Resolution:0.01 lx
BIT Glare 2	Thermistor	DS18B20
	Illuminance sensor	OPT3001 [21] Includes optical filter to match human eye response Range:0.01–83 k lx
	HDR imaging device	Under development – not included
BIT Station 2	Illuminance sensor	OPT3001 [21] Includes optical filter to match human eye response Range:0.01–83 k lx
	CO_2 non-dispersive infrared sensor	Cozir A [22] Range:0–2000 ppm Precision: ±50 ppm Accuracy: ± 30 ppm Resolution: 1 ppm
	Air temperature sensor	Cozir A [22] Range: 0–55 °C Precision: ± 1 °C Resolution: 0.1 °C ppm
	Humidity sensor	Cozir A [22] Range: 0 to 95 % Precision: ± 5 % Resolution: 0.1 °C ppm

Appendix B. Statements displayed on the mobile-app questionnaire for capturing occupant satisfaction

- To what extent do you agree with this sentence (1 strongly disagree to 5 strongly agree):
    1. I feel well with my workload
    2. I like my office space
    3. I feel happy
    4. I feel well-rested
    5. I am satisfied with my level of fitness
    6. I feel productive
    7. I find easy to concentrate
    8. I find the thermal environment satisfactory
    9. I find the daylight in the office satisfactory
    10. I am satisfied with the outdoor view from my desk
    11. I don't have glare in the office
    12. I find the control of the environment satisfactory
    13. I find the air quality in the office satisfactory
    14. I find the acoustic environment in the office satisfactory
    15. I feel familiar with the office space
    16. I am enjoying my work task
- For how long have you been sitting at the desk?
- Please feel free to leave a comment

Appendix C. Details of the statistical model

Table 8 shows the independent, covariate and dependent variables considered in the experimental design. Covariates are independent variables that can influence the outcome of a dependent variable, but they are not of direct interest. Potential covariates were considered, either by measuring and including them as variables in the experimental design, or by balancing them across the experiment. The outdoor temperature was considered as covariate variables. Time of the day and orientation of the façade are also potential covariates, but all the volunteers were exposed to the same orientation and for a whole day in all the scenarios. Therefore, time of the day and orientation of the façade were excluded as covariates.

A linear mixed model [23] was used to assess the significance of the difference in satisfaction across a given experimental scenario, considering the covariates and the independent variables. When the interaction between covariates was not significant, it was removed from the model. When significant, post-hoc comparisons were performed, in order to evaluate the effect of the interaction term. Details of the statistical analysis are reported in Appendix B.

A linear mixed model [23] was used to assess the significance of the difference in satisfaction across a given experimental scenario. Linear mixed models are a type of regression model that takes into account both variation that is explained by the independent variables of interest (the "fixed effect factor") and variation that is not explained by the independent variables of interest, called "random-effects factors". "Random-effect factors" depends on the individual differences between volunteers and they are particularly important when volunteers are a random sample of a large population. The identification code of each volunteer was used to describe in the model the "random-effect factors". The programming language "R" [24] and the function "lmer" [25] were used to perform the analysis. The covariates were also tested for multi-collinearity using the Variance Inflation Factors (VIF) and the "R" function "Caret" [26]. In the model, the scenario (1, 2 or 3) was included as a "fixed effect factor" on the levels of environmental satisfaction, perceived levels of productivity, ease of concentration and contentment of the office space.

The linear mixed model also allows to include the interaction between covariates and independent variables, which means that each combination of covariates and independent variables is considered to affect differently the outcome of the model. When the interaction term was assessed as not significant, it was removed from the model. When significant, the R function "emmeans" [27] was used to perform post-hoc comparisons, applying the multiplicity adjustment Tukey's HSD to control for false discovery rate, in order to evaluate the effect of the interaction term.

Appendix D. External conditions

Fig. 23 shows the outdoor temperature and solar radiation distribution during the scenarios. The period 1 was characterised by a higher average outdoor temperature than the period 2 and 3, while the levels of solar radiation of the scenarios 1 and 2 were similar. The scenario 3 had lower levels of solar radiation.

Table 8
Variables considered in the experimental design.

Independent variables	Covariates (measured/included)	Covariates (balanced)	Dependent variable
Type of control	Level of habituation Enjoyment of task Level of happiness** Level of workload Level of rest Outdoor temperature Outdoor temperature	Gender Order	Thermal satisfaction Visual satisfaction Air quality satisfaction Acoustic satisfaction Personal control satisfaction Level of perceived productivity Level of concentration Contentment with the office space Number of discomfort events Number of interactions

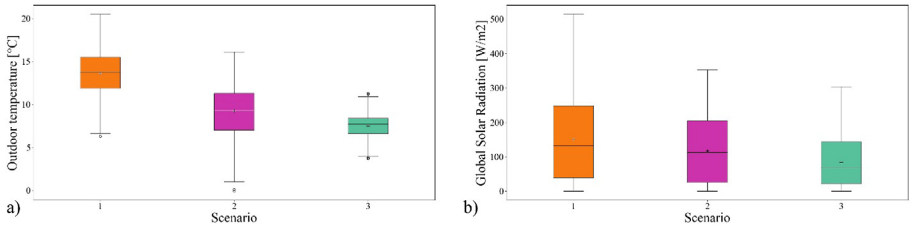

Fig. 23. External weather during the scenarios: a) plot of the outdoor temperatures; b) plot of the global solar radiation. The rectangle represents the second and third quartiles of the data distribution, the whiskers shows the lower and upper quartile, the data points represent the outliers, the cross represents the arithmetic mean and the horizontal line the median.

Appendix E. Overall satisfaction in the morning and evening

Fig. 24 and Fig. 25 shows the average levels of satisfaction during the morning and the evening.

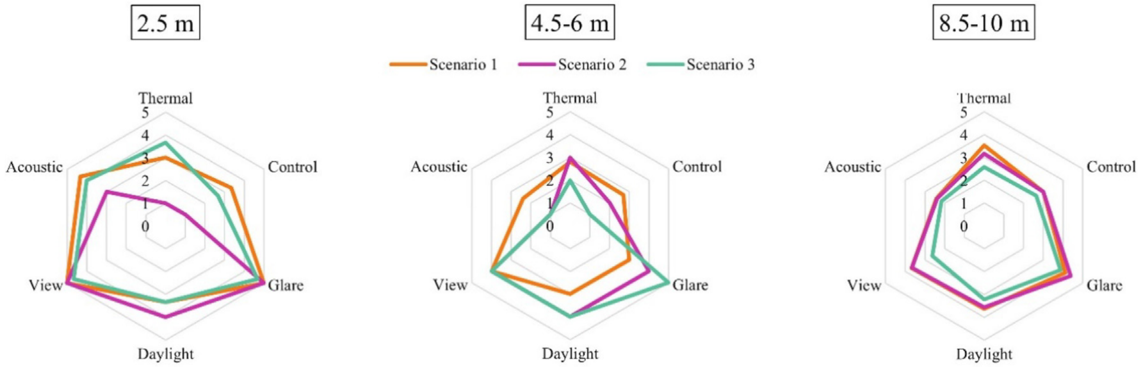

Fig. 24. Spider plot of the average environmental satisfaction at the three different distances from the façade during the morning (09:00–12:00 hrs).

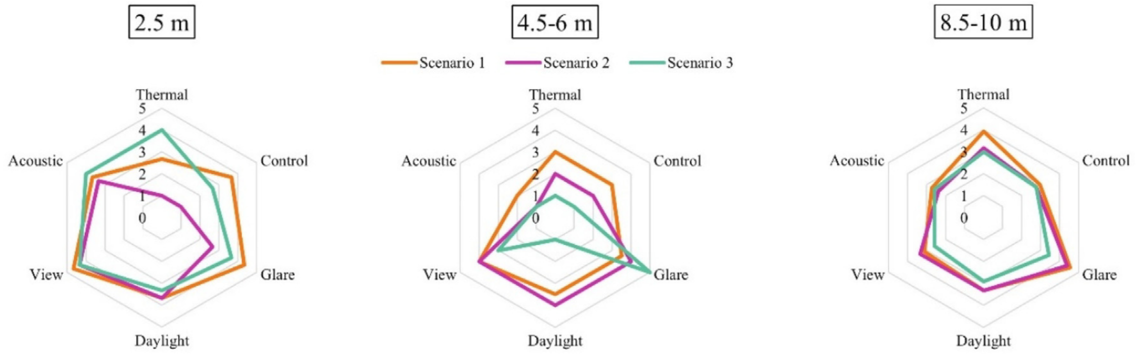

Fig. 25. Spider plot of the average environmental satisfaction at the three different distances from the façade during the evening (15:00–18:00 hrs).

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