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The influence of occupant behaviour on the energy performance of single office space with adaptive facades: simulation versus measured data

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Abstract

The study investigates the impact of occupant overrides on the energy and daylight performance of an adaptive blind control strategy.

Firstly, experimental data is collected in a controlled office environment where occupants are exposed to manual and automated control scenarios. Secondly, results from a calibrated energy model of the same office environment are used to predict the energy and daylight performance of both scenarios. Actual and predicted energy performance are then compared to evaluate the impact of occupant behaviour on energy and daylight performance.

The results indicate that occupant behaviour (OB) in respect to blind operation has an impact on the predicted performance of an adaptive façade control strategy. Hence, they confirm the need for new models that can adequately describe the influence of OB on adaptive façade control strategies.

Key Innovations

- Measuring the energy performance gap of an automated façade control strategy due to occupant behaviour

Practical Implications

- Endorsing the use of occupant behaviour models when evaluating the performance of adaptive façade control strategies

Introduction

Adaptive shading devices have a significant potential to improve occupant comfort whilst reducing energy consumption in buildings. However, their application is still limited. One of the reasons is the scarcity of established simulation methods that can demonstrate their potential against traditional solutions during the design phase (Loonen, Favoino, Hensen, & Overend, 2017). For instance, the assumptions made on occupant behaviour (OB) in the simulation workflow affect the energy performance of the adaptive control strategy (Gaetani, van Woensel, Hoes, & Hensen, 2020). In addition, the available literature on occupant interaction with adaptive shadings shows that occupants often override adaptive façade controls (Bakker, Oeffelen, Loonen, & Hensen, 2014). Therefore, including OB in the simulation workflow is crucial when evaluating alternative control strategies for shading devices since the optimal control scenario depends also on occupant interaction and overrides. Previous work has already demonstrated that occupant interactions with manually controlled blinds have an impact on the energy performance of buildings (Buso, Fabi, Andersen, & Corgnati, 2015; Hoes, Hensen, Loomans, de Vries, & Bourgeois, 2009) and that occupancy patterns also affect adaptive control strategies performance (Gaetani et al., 2020), but there is a dearth of research on the use of existing or novel occupant behaviour models when assessing adaptive façade performance during the design stage.

In this paper, the importance of including appropriate OB modelling in the simulation workflow is demonstrated by comparing the measured and predicted energy performance of an office space. Firstly, experimental data is collected in an office space where two blind control scenarios are implemented. In the first scenario the blinds are manually controlled by the occupants. In the second one, an adaptive blind control strategy is implemented whilst still allowing occupants to override the controls. In both scenarios, data on energy consumption, daylight performance and occupant interaction with the internal venetian blind is collected.

Secondly, a calibrated energy model of the same office environment is used to evaluate the mismatch between the predicted and actual energy consumption in both scenarios. The interaction of occupants with the internal blinds is then discussed as the cause of discrepancy between the actual and the measured energy consumption.

Methodology

Description of case study

Figure 1 shows the case study: an office-like laboratory for occupant comfort and interaction research in Cambridge (UK) called MATELab (Luna-Navarro et al., 2018). MATELab was chosen since it is a privileged space for in situ multi-domain assessment of occupant perception of, and interaction with, alternative control strategies for adaptive facades. In this sense, this space allows to experimentally measure occupant interaction with the facade, daylight performance and energy consumption. MATELab is an office space of

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approximately 30 m^2 with a south-oriented glass façade, composed of two façade bays and an internal venetian blind (Figure 2). The characteristics of the building envelope are reported in Table 1. The internal blinds have a reflectance of 0.65 and the width of the slat is 0.035 m.

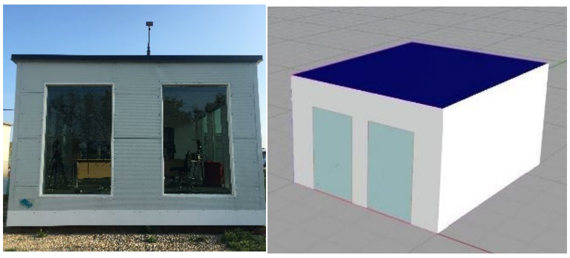

Figure 1 Front view of MATELab (left) and model view (right)

Figure 2 a) Internal view of MATELab without occupants and b) with occupants.

The HVAC system is composed of an external heat pump with a heat exchanger that supplies fresh conditioned air to the office by an under-floor air distribution (UFAD) system. The exhaust air is then extracted by ventilation grids in the ceiling. The air velocity in the room is low and in average under 0.05 m/s. The lighting system is a LED system that can be dimmed according to the sensor on the ceiling.

Table 1: Characteristics of the Building Envelope

Element	U-value [W/m²K]	SHGC	Visual transmittance
Floor	0.15	-	-
Roof	0.10	-	-
Opaque wall	0.175	-	-
Glass facade	1.1	0.31	0.50

Experimental scenarios

The following experimental scenarios were implemented:

- **Scenario 1** Manually controlled blinds. The internal blinds are only controlled by the occupant.
- **Scenario 2:** Automated control of blinds with possibility of occupant override.

In both scenarios, the lighting and the HVAC were controlled by an automated control system according the setpoints in Table 2 and, occupant override of the lighting and the HVAC was never allowed.

One volunteer per time was invited to spend a whole working day in the test room for two consecutive days. The occupant was positioned at 1.5 m from the left façade bay, as shown in Figure 2b. The order in which occupants experienced the two control scenarios was randomised in order to avoid potential bias. On the first day, the participant experienced either the manually or automated controlled scenario, while in the second day they experienced the alternative scenario. A total of 8 volunteers (4 female and 4 men) participated in the experiments. Volunteers were asked to perform their normal work tasks and to use their personal laptop. They were left alone and undisturbed in the office while the researcher was in adjacent office for the whole experimental day. In a previous study (Luna-Navarro A.; Overend M., 2021) the authors had already investigated how occupant habituation with MATELab changed in time during the same experimental days reported in this paper. In addition, they also evaluated how different volunteers had perceived MATELab in comparison to a typical office space. Data on habituation and occupant perception was gathered through mobile-apps. The same app was also used in this paper to collect information on the rationale behind any occupant interaction with the façade (see section on *Occupant-related data collection*). They were asked about their level of agreement with the following statement: "I feel habituated with the office space". Overall, on average volunteers felt habituated (Level of agreement = 5) after one hour. In addition, the volunteers were also asked at the end of the day to what extent they felt the office space was similar to a typical office space. Figure 3 shows that the volunteers were on average considering MATELab similar to a typical office space.

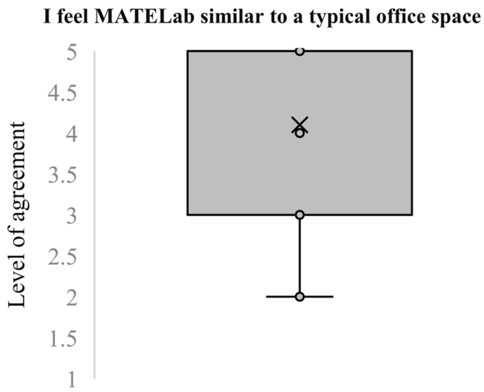

Figure 3 Level of agreement of the volunteers with the statement "I feel habituated with an office space" after (Luna-Navarro A. Overend M., 2021)

The experiment took place during September 2020 and when the sky was either clear or mid-cast. Experiments never took place when the sky was overcast.

A weather station on the roof was used to monitor the weather (including beam and global horizontal solar radiation, vertical solar radiation and outdoor temperature

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and wind speed). The indoor environmental quality at the proximity of the occupant was monitored by an indoor air and globe temperature sensor, an air flow metre and a horizontal illuminance sensor on the occupant desk. The occupant could adjust the internal blind by either controlling the height of the blinds (two positions allowed: fully raised or fully down) or by tilting the angle (from 0° to 90°). The control was operated by a switch beside the window and reachable by the occupant without standing up. In addition, since knowledge on the rationale behind an automation strategy helps to increase user acceptance (Meerbeek, de Bakker, de Kort, van Loenen, & Bergman, 2016), volunteers were informed that the control strategy was operating to minimise the energy consumption for lighting and HVAC. At the beginning of each experimental day, the blinds were in the default position, which is fully down with a slat angle of 90° (horizontal position).

Table 2 Setpoints of the artificial service

Artificial service	Setpoints
HVAC - Cooling	25 °C from 7 am to 5 pm
HVAC - Ventilation	50 l/s minimum
Lighting	450 lux on desk when room is occupied

Figure 4 shows the daily average global solar radiation on the vertical façade (ranging 0 to 600 W/m), while Figure 5 shows the average daily outdoor temperature, which was between 12-20 °C. Figure 6 shows the indoor air temperature distribution at the centre of the room during the manual and the automated scenario.

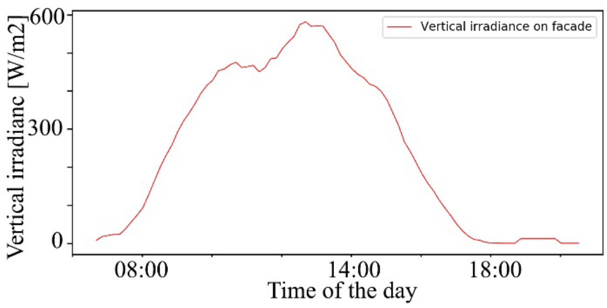

Figure 4 Average global solar radiation on the vertical façade during the experimental days

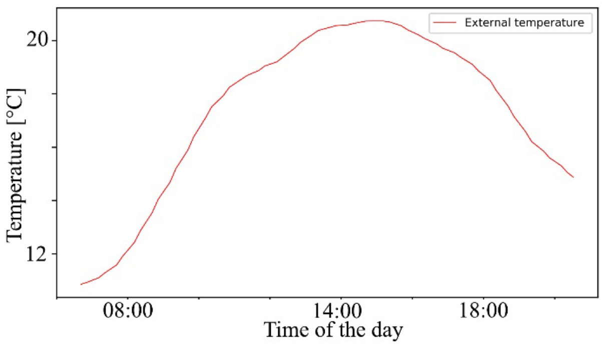

Figure 5 Average daily outdoor temperature during the experimental days

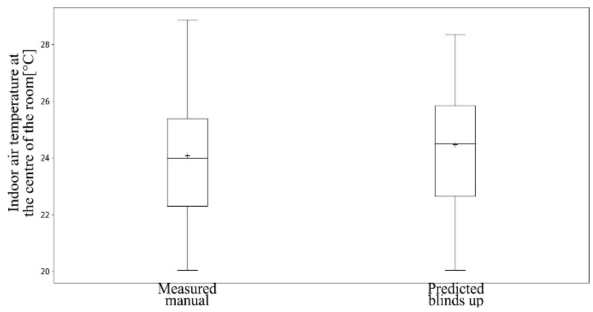

Figure 6 Indoor air temperature distribution during the manual and the automated experimental scenario

Control strategy of the internal venetian blinds

The control strategy was based on the global solar radiation incident on the south vertical facade, measured by the weather station on the roof. A schematic diagram with the control strategy is shown in Figure 7. The control was programmed to raise the blinds when the measured solar radiation was below the desired threshold for more than 15 minutes, conversely when the solar radiation was above the threshold for more than 15 minutes, the control would lower the blinds to prevent overheating and minimise cooling energy demand.

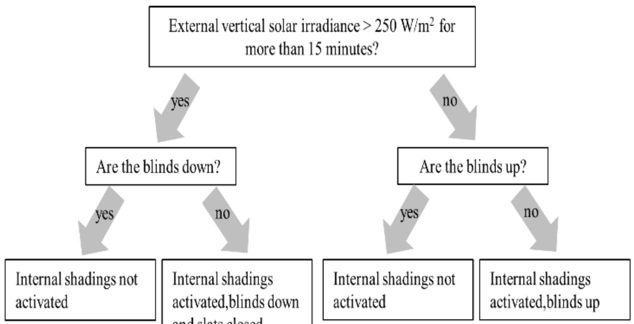

Figure 7 Algorithm description of the control strategy for the internal venetian blinds

The tilt angle of the blinds follows the sun elevation in order to block the direct solar radiation to enter the room.

Occupant-related data collection

Data on occupant interaction with blinds was collected in two ways:

1. Monitoring occupant control actions by using the control system, which can track the override actions performed by the user even when the blinds are not automated.
2. Questionnaire through a bespoke mobile app that occupants were asked to use every time they would interact with the blinds. The same app was also used every two hours for information regarding their perception of the environment. Information on occupant perception of the IEQ is not described in this paper since it is part of previous work (Luna-Navarro A., Overend M., 2021).

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Simulation procedure

Table 3 Setpoints in the simulation model

System	Simulation model
Occupancy	1 Occupant from 10 am to 5 pm
HVAC services	HVAC On from 7 am to 5 pm and $T_{setpoint}$ at 25 °C
Lighting services	Reference Point Illuminance on the occupant desk with a target illuminance of 450 lux

The energy performance model was developed in EnergyPlus version 9.3 (Doe, 2013) and calibrated with experimental data in a previous study (Luna-Navarro A., Borkowski E., Michael M., Rovas D., Raslan R., n.d.). A bespoke weather file was created for the simulation scenarios by using the data collected by the weather station and using the software Elements (Big Ladder Software, 2016).

Due to the blind typology, no existing OB model that describes the interaction between occupants and blinds could be implemented to mimic the actual behaviour. For example, Haldi and Robinson (Haldi & Robinson, 2010) allows for partial discretization of the blind opening, but does not account for the possibility to change the tilt angle. Conversely, in our case study blinds are only lowered or raised, while most of the occupant interaction concerned changing the tilt angle.

The automated control of the internal blind was implemented in the EMS of EnergyPlus according to a previous work (Borkowski, Luna-Navarro, Overend, Rovas, & Raslan, n.d.). In this study, the EMS feature was used to provide high-level, supervisory control in combination to the WindowProperty:ShadingControl object in EnergyPlus. The slat angle is controlled by the function BlockBeamSolar within the ShadingControl, while the EMS Control strategy was used to raise or lower the blinds according the control algorithm in Figure 7. In both the experimental scenario and the simulation model, both façade bays are controlled at the same time by the automation strategy. Only in the experimental scenario, occupants can also decide to override one façade bay at the time.

For the internal gains due to electrical appliances a value of 24 W/m^2 for the power consumption was considered. These internal gains were monitored in the experimental phase through the power metres dedicated for the plug loads. For the artificial lighting in LED a value of 0.7 W/m^2 was used.

Simulation strategy

Since no existing OB model was deemed appropriate, the two experimental scenarios were simulated according to the two different strategies that are described in Table 4 . The manual scenario was simulated considering the blinds always up, since this scenario will have the maximum level of solar gains and therefore be the worst case to predict the energy consumption in terms of electricity demand for the HVAC (cooling mode).

Both thermal models were calibrated in previous work from the authors by using the indoor air temperature as control parameter and against benchmark scenarios where no occupants were present. Once calibrated, both models had a Coefficient of Variation of the Root Mean Square Error (CVRMSE) below 10% and therefore they were deemed compliant with the ASHRAE 140 (ASHRAE, 2014).

Table 4: Description of the simulation strategy according to the experimental scenario

Experimental scenario	Simulation strategy for blind control
Manual control scenario	Strategy 1 Blinds always up (worst case scenario)
Automated control scenario	Strategy 2 Automated control with no overrides (No OB model)

Performance indicators

The simulation strategies were assessed according the following Performance Indicators (PIs):

- **Daily Electricity demand for the HVAC [kWh/day];** This was measured in the experiment by a power metre located at the power input of the HVAC system and predicted in the model by using the “Facility Total HVAC Electricity demand” output.
- **Daily Electricity demand for Lighting [kWh/day];** This was measured in the experiment by a power metre located at the power input of the Artificial Lighting and predicted in the model by using the “Zone Electric Lights Power” output.
- **Daylight Autonomy (DA)**; This was measured by an illuminance sensor on the desk of the occupant and by subtracting the contribution of the artificial lighting. In the model was also calculated at the reference point located at the centre of the occupant desk. The DA is expressed in occupied time fraction when the indoor illuminance is > 300 lux (Walkenhorst, Luther, Reinhart, & Timmer, 2002).

Results and discussion

Measured occupant interactions vs predicted

Figure 8 shows the measured blind movements of the façade during the manual experimental scenario (Figure 8 A and B) and the automated one (Figure 8 C and D). Figure 8 E shows the predicted blind interaction without considering occupant overrides. As shown in Figure 9, during the manual experimental scenario, the blinds were left down with horizontal slat for the majority of the time (91% of the time for the right façade bay – the further from the occupant, 89% for the left side – the closest from the occupant), confirming previous research stating that occupants do not often interact with the manual blinds (Van Den Wymelenberg, 2012). In the automated

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experimental scenario, the blinds were left down for a lower amount of time (73% of the time for the right façade bay and 66% of the time for the left façade). This was due to the automated control, which raised the blinds when the vertical solar radiation was below the energy performance threshold, but also because occupants interacted more frequently with the blinds than in the manual scenario. The calibrated thermal model predicted instead the blinds to be down for a longer amount of time for both facades (72%), similarly to what happened in the experiment for the right façade bay, which being further from the occupant had a much lower interaction with the occupant and therefore a better agreement with the predicted data. Figure 10 shows the number of times users interacted with the blinds during the manual and automated experimental scenario and the reason why they did so. In total, during the automated experimental scenario, occupants interacted 25 times with the blinds (see Figure 10), while in the manual scenario they did so only for half as much (only 13 times). Occupants overrides of the automated controls were equally distributed between lowering and raising actions. In the manual scenario, the first two occupants were more active in interacting with the blinds, while the other occupants left the blinds unchanged.

Daily energy demand for HVAC and Lighting

The mismatch between expected and actual blind position had an impact on the accuracy of the predicted energy consumption for the HVAC and the artificial lighting.

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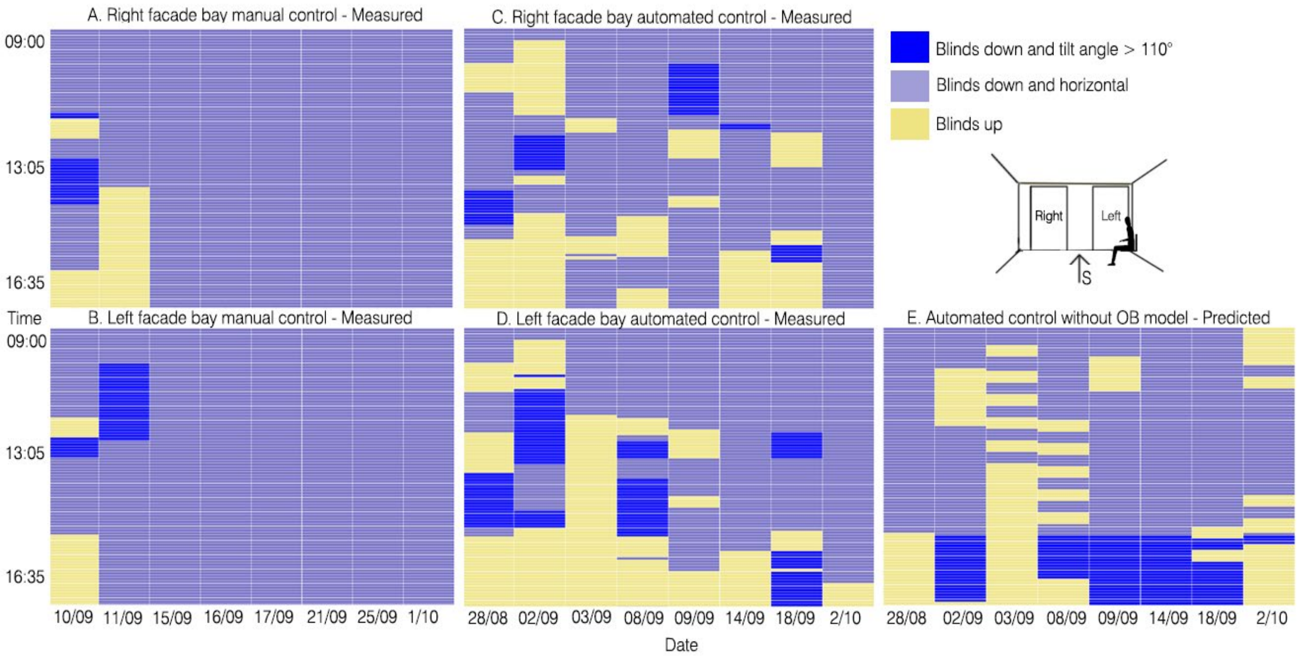

Figure 8 Blind position measured during the experimental days with manual control (A for Right Facade and B for Left Façade), with automated control (C for Right Façade and D for Left Façade),and predicted with Automated control and without OB model (E).

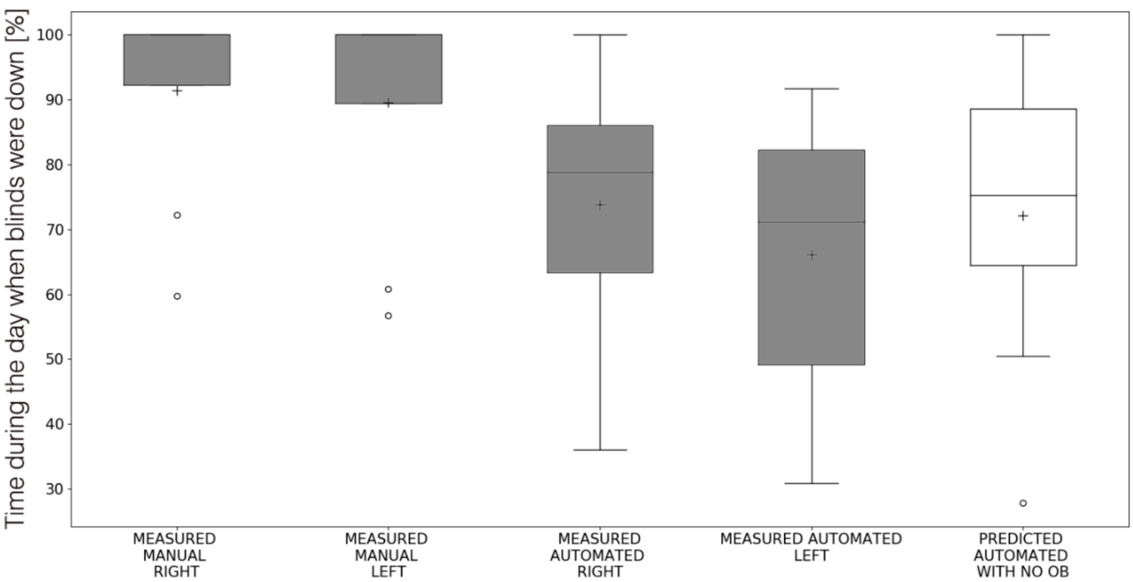

Figure 9 Percentage of time during the day when blinds were down per scenario

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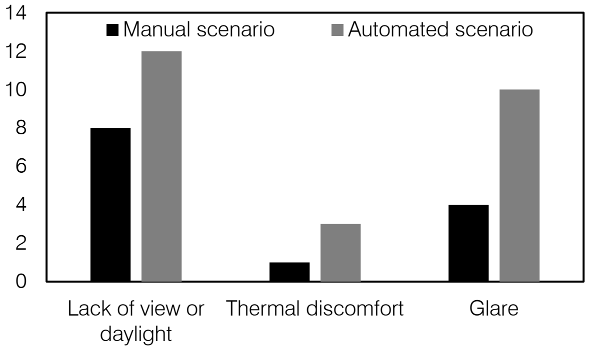

Figure 10 Reasons for user blind interaction in the manual and automated scenario

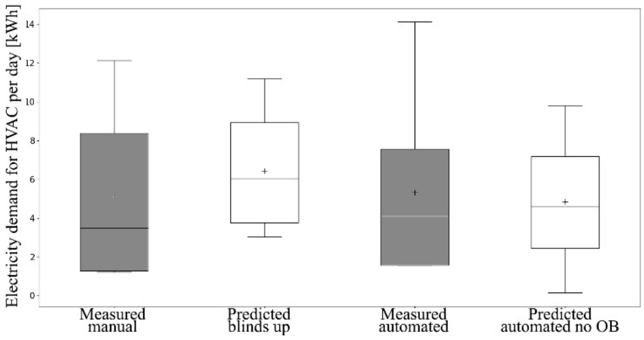

Figure 11 HVAC Electricity consumption per day

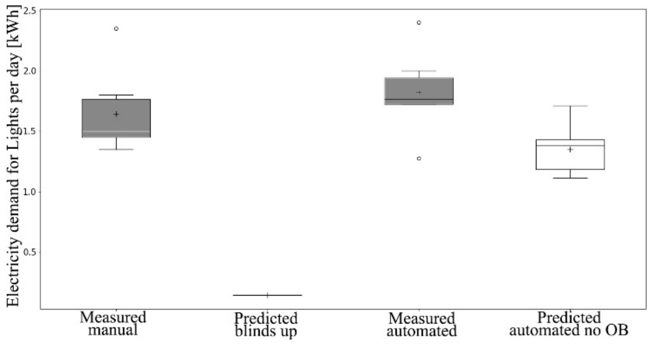

Figure 12 Lighting consumption per day per scenario

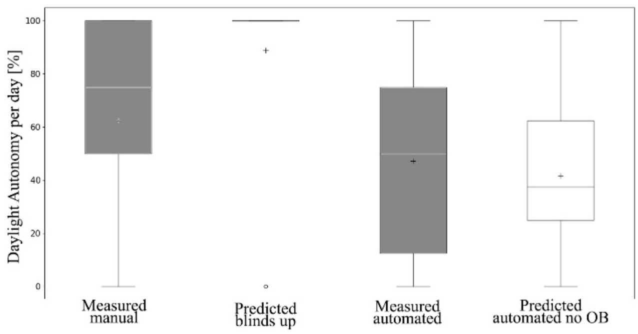

Figure 13 Daylight Autonomy per day [%]

The average HVAC electricity demand per day in each scenario is shown in Figure 11. The average predicted demand of the scenario with the automated blind control (4.84 kWh/day) was lower than the average predicted electricity consumption in the manual scenario (5.14 kWh/day). This result could have incorrectly informed the choice of automated control strategy over the manual control. However, the actual measured energy consumption in the experimental scenario with automated blind control showed to be actually higher than in the manual scenario (5.33 kWh/day) and to have a much higher peak (up to 14 kWh/day). During the design phase. This result could have led to an underestimation of the design loads of the HVAC. The scenario with blinds always up would also have incorrectly informed the design of the HVAC load, since it showed average of 6.44 kWh/day, but also a lower peak in energy demand. In both the manual and automated blind control scenario, the predicted energy consumption would not have adequately informed the design of the HVAC power supply.

Figure 12 shows the electricity demand for lighting. The measured electricity consumption for lighting was lower than in the scenario with automated blind control. This finding was due to the fact that the blinds were often left down but in the horizontal position, whereas in the automated blind control strategy the blinds were more often fully-closed to prevent discomfort glare. This also explains the reason why the predicted lighting energy demand was lower than the actual measured one, since occupants lowered the blinds system due to thermal discomfort or glare. Similarly, therefore the Daylight Autonomy (DA) was lower in the measured automated scenario than in the measured manual scenario (47% vs 63%), as shown in Figure 13. The predicted DA for the automated blind control scenario was also lower than the measured one because occupants often raised the blinds to increase the daylight or the view level.

Discussion and Conclusion

The paper discusses the importance of OB modelling when evaluating the daylight and energy performance of an automated blind control strategies. These preliminary results showed that the energy performance of automated blind control strategies could be overestimated by non-considering occupant overrides and, therefore, underestimating the associated energy loads for lighting and HVAC. Future work is needed to consolidate these results and provide an alternative simulation workflow that can adequately integrate OB with automated and/or adaptive blinds.

For instance, future work will address the limitations of this study. Firstly, the experimental data was only collected during eight days per experimental scenario, but a larger experimental campaign is required to gain statistical significance on the results and understand the impact of OB on the annual energy performance of a blind control strategy. Secondly, when modelling OB with automated blind control strategy is important to couple the thermal energy model with a raytracing daylighting model (Luna Navarro et al., 2020) to accurately predict the frequency in which occupants interact with blinds. This is because occupant overrides of automated blind controls are often due to lack of daylight, discomfort glare or thermal discomfort from

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direct solar radiation and, therefore, it is crucial to simulate the location of the solar beam across the floorplan. For complex control strategies and occupant behaviour models, a co-simulation approach is also needed to adequately model the automated strategy and overcome the limitations of EnergyPlus (Taveres-Cachat, Favoino, Loonen, & Goia, 2021). Future work will also consider potential shading schedules that could be used to predict the energy consumption with manual dynamic venetian blind that can tilt the angle.

Lastly, diversity patterns also play an important role in predicting the extent of occupant override of the automated control system (e.g. active vs passive users) (Gaetani et al., 2020), as shown by the different interaction preferences reported during the first two days in the manual scenario.

Nevertheless, this preliminary work confirms the need for novel occupant behaviour models to adequately estimate the impact of user override when evaluating the performance of alternative adaptive and/or automated control strategies for venetian blinds.

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