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Targeting modular adaptive façade personalization in a shared office space using fuzzy logic and genetic optimization

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ABSTRACT

In shared office spaces, occupants' comfort criteria are limited to locally controlled zones while ambient features of the environment and the potential negative impacts of others' behavior require a well-designed control system, especially over adaptive façade elements. This means setting up control strategies for a wider spectrum of varying comfort perceptions from person to person dictates an approach towards personalizing adaptive facades. Thereby, this research coupled a simulation-based methodology with fuzzy logic and a genetic algorithm to personalize façade modules based on the visual discomfort conditions of the occupants. Results confirmed that increasing the control freedom by personalization accounting for multi-objective criteria including glare, daylight, and view could satisfy occupants from 83% to 100%. Moreover, the proposed façade personalization framework could enhance visual comfort compared with two typical automated Venetian blind controls, significantly. This study provides novel insights for designers and operators to decentralize facades' elements by accepting occupants' feedback as part of their control loops.

1. Introduction

1.1. User-façade interaction

As one of the aspects of indoor environmental quality, visual comfort plays a significant role in providing user satisfaction and well-being. Several factors are associated with maintaining visual comfort within spaces, including illuminance level, glare protection, and view to outdoors, all of which are capable of being controlled in indoor spaces. The positive effect of proper daylighting and window features related to outdoor view on occupants' well-being, health, and performance has been widely assessed [1]. It has also been shown that the sense of control over the indoor environment leads to higher user satisfaction levels in the workplace [2,3] and executive control can decrease work stress levels [4]. Furthermore, controllability has been reported as one of the factors affecting the well-being and problem-solving performance of workers [5]. Utilizing suitable adaptive systems in building facades is found to be beneficial not only in terms of visual comfort but also energy efficiency and thermal comfort [6]. Many efforts have been done to study the typologies of adaptive façades [7–10] and a recent review defined it as "*a composition of responsive elements to adjust the façade either*

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automatically or manually based on the environmental changes or/and user preferences" [11]. The automated control strategies have shown many advantages regarding energy saving and visual/thermal comfort ([12–16]); however, there is the risk of causing user distraction and discomfort, particularly when the transitions in façade configuration occur at higher frequency [17]. It has been investigated that sense of control over physical environmental aspects, such as opening the windows and regulating HVAC and lighting systems, can lower the user's mental, visual, or acoustic distraction related to loss of concentration in office workplaces [18]. More specifically regarding the user interaction with adaptive facades, it has been shown that occupant satisfaction elevates with the occupant manual or override control ([19–21]). In addition to higher levels of user satisfaction, occupants tend to utilize daylight more in offices with easy manual controls, leading to less lighting energy consumption [22]. The investigations regarding user-building interaction have revealed the pattern of user control on shade positions [23] and the energy implications of blind use [24]. The user-façade interaction is not affected only by the environmental conditions, as human attributes have been found to be a significant factor in predicting the shading and subsequently lighting controls [25]. Meanwhile, the occupant-façade interaction is a challenging multi-disciplinary subject due to the need for satisfying energy efficiency, providing indoor environmental quality, and addressing the individual user comfort in a shared space ([26–28]). Nevertheless, there are some challenges during the operation phase of buildings with adaptive facades regarding overheating, glare, and personal control conflicts [29] which reveal the necessity of implementing personalized/occupant-centric control (OCC) strategies in buildings with adaptive facades.

1.2. Occupant-centric control of adaptive facades

By understanding the occupant's thermal/visual preferences based on the gathered data from the occupants and physical environment, the OCC strategies are implemented to balance between the intended objectives, namely, energy efficiency and thermal/visual comfort. These strategies can range from simple manual controls to more advanced predictive models [30]. Based on a review of the field-implementations of OCCs conducted by Park et al. [31], the term has been classified into two sub-categories of 'occupancy-centric' and 'occupant behavior-centric'. The former sub-category focuses on the control strategies based on occupant presence/absence in the space, whereas the latter considers the occupant's visual/thermal comfort.

Several previous studies have investigated the effect of implementing OCC strategies on the buildings' energy use and occupants' comfort levels. The influence of applying OCC strategies in the Heating, Ventilation, and Air-Conditioning (HVAC) systems on energy efficiency, thermal comfort, and indoor climate has been a relatively active area of research ([32–37], and [38]). The occupants' visual comfort has also been assessed as another objective alongside thermal comfort when implementing OCC strategies. In a study conducted by Ouf et al. [39], different OCC strategies in an office space were tested using a simulation-based method to mimic real-life occupant behavior scenarios. Indoor illuminance level and indoor temperature were assumed to be the indicators of the occupants' visual and thermal preferences affecting the probability of light switches and thermostat setpoint changes. Results showed a possibility of more than 80% variation in total electricity use, and the minimized energy value was achieved when the assumptions of tolerant occupant behavior were combined with the OCC strategies. Based on a 6-week study in 10 offices, Nagy et al. [15] reported a reduction in energy consumption by up to 37.9% when implementing an adaptive occupant-centric lighting control strategy compared to a standard setting control baseline with no active controller after office hours. In another research, a user study on the performance of implementing OCC in six offices was conducted under the real condition with 10 occupants for a duration of 12 weeks. Results also showed a reduction in energy consumption by an average of 13.4% without a considerable comfort alteration [16].

The focus of a few previous studies on this topic was to not only evaluate the building energy performance when applying OCC strategies but also to optimize the energy efficiency and occupants' comfort. In the context of a daylit office space with an automated shading system, Xiong et al. [40] presented a method in which a multi-objective optimization of personalized visual satisfaction and lighting energy use is applied. The results indicated that the lighting energy use can be varied from 1 to 9.3 kWh/m^2 depending on the user's visual preferences, assuming the work plane illuminance target of 500lx. Considering the same aim of lowering lighting energy without compromising the occupants' visual comfort in open-plan offices, Kar et al. [41] proposed a recommender system that learns user preferences to control task lights. The approach was developed using Python, and the test experiment showed the potential of up to 72% reduction in the lighting energy. In another study, Khorasani-Zadeh and Ouf [42] used a genetic algorithm with the objectives of minimizing the annual energy consumption while maximizing visual and thermal comfort to optimize OCC strategies' performance, while considering stochastic occupant behavior with different preferences. The proposed framework showed up to 33% energy reduction and 28% comfort improvement in optimized conditions compared to a baseline scenario. In a shared office space with a non-conventional adaptive façade, Tabadkani et al. [43] proposed a real-time personalization strategy, considering both energy-saving and visual comfort parameters as the objectives. Compared to the two most commonly used automatic shading controls, authors reported an improvement of 61% and 29% in visual comfort performance and thermal energy demand, respectively.

Investigating the application of computer vision and machine learning methods in the OCC strategies has been also an active area of research. The computer vision-based occupant information sensing systems for OCC strategies were reviewed by Choi et al. [44]. Highlighting a scarcity of studies in this area, authors reported a median of 28% and 17% energy-saving potential based on occupancy-related and comfort-related building control by implementing this approach, respectively. The OCC strategies implemented specifically with regard to the building facades and by using machine learning methods have been studied in a few previous papers. For instance, Kou et al. [13] used the machine learning approach to learn the relationship between occupants' behavior and environmental condition with the aim of developing an integrated lighting and shading control strategy. The proposed method led to a preference profile for each user, regulating shading and lighting systems. Developing a more comprehensive shading control system, Lou et al. [45] decentralized the blinds using machine learning to evaluate visual comfort, daylighting, energy saving, and solar heat gain within an open-plan office. The proposed strategy using the surrogate model technique resulted in considerable reductions in DGP (Daylight Glare Probability) and assured the target illuminance at up to 96% of occupied task planes, as well as noticeable reductions in lighting

loads. To estimate glare and thermal discomfort based on occupants' postures, Wang et al. [46] developed a deep learning model using convolutional neural networks (CNN) which regulates the adaptive facades modules and HVAC system. Trained by 1260 videos, the proposed model was able to recognize 13 occupant postures, allowing the occupant-centric contactless comfort evaluation. Based on Reinforcement learning, Park et al. [47] introduced an occupant-centered lighting controller, which was experimented in five offices during eight weeks. By learning both the occupant preferences and indoor environmental conditions, the experiment showed the applicability of the approach by providing an appropriate balance of energy-saving potential and occupant comfort.

In the mentioned studies, the OCC strategies were investigated in offices without façade shading ([15,16,39,41]), with the typical roller or blind shading devices ([13,40,42,45]), or with modular adaptive façade ([43,46]). Moreover, the related control strategies were mostly established based on the preferences or thermal/visual comfort of one representative occupant with different visual preference scenarios ([13,39,40,46]), or based on a number of occupants ([15,16,41,43,45]). Accordingly, studies on the topic of implementing OCC strategies in shared office spaces with adaptive façades and including more than one user are relatively rare. It is also beneficial to address multiple aspects of the occupants' visual comfort, namely illuminance level on the task plane, glare probability, and view to outdoors when trying to optimize the performance of adaptive facades based on OCC strategies. However, these three indicators have not been simultaneously included in the assessment of adaptive facades in the previous studies. There are other points to heed when investigating the users' visual preferences in a shared office space with an adaptive façade rather than private offices [20]. In the first place, not all typologies of adaptive facades such as biomimetic facades can accept OCC strategies [11]. Also, providing visual comfort condition for all occupants in a shared office space is challenging due to individual visual preferences, social constraints and hesitations, different positions and distances to the fenestrations, and distinct angles to the outdoors [13]. In such cases, several studies confirmed that the users could easily ignore the automated control strategies [43,48]. Therefore, it is necessary to incorporate spatial control systems that enable interactions between the building and the occupant. Among building façade typologies, modular adaptive facades are a promising solution for decentralized control as opposed to Venetian blinds or roller shades, despite their control complexity [49].

1.3. Research objectives

Based on the relevant previous studies, more attention has been given to assessing occupant-centric control strategies in offices with conventional shading system (e.g., Venetian blinds, roller shades), mostly considering one or multiple comfort aspects in single office spaces which are not applicable in shared spaces where occupants prefer to control over their local environments and generalized comfort measures might not satisfy individuals' desires. This is mainly because of the existing diverse visual comfort perceptions from one occupant to another require an integrated building façade control management system. Thus, this study targets the modular façade personalization in a 'shared space' to address the existing potential visual comfort conflicts among users due to social constraints and hesitations and their daily stochastic preferences. To this end, the main objectives of this research are:

- To perform simulation-based evaluation of a modular adaptive facade and its impact on users' visual comfort as a combination of task illuminance, vertical eye illuminance, and view to outdoors;
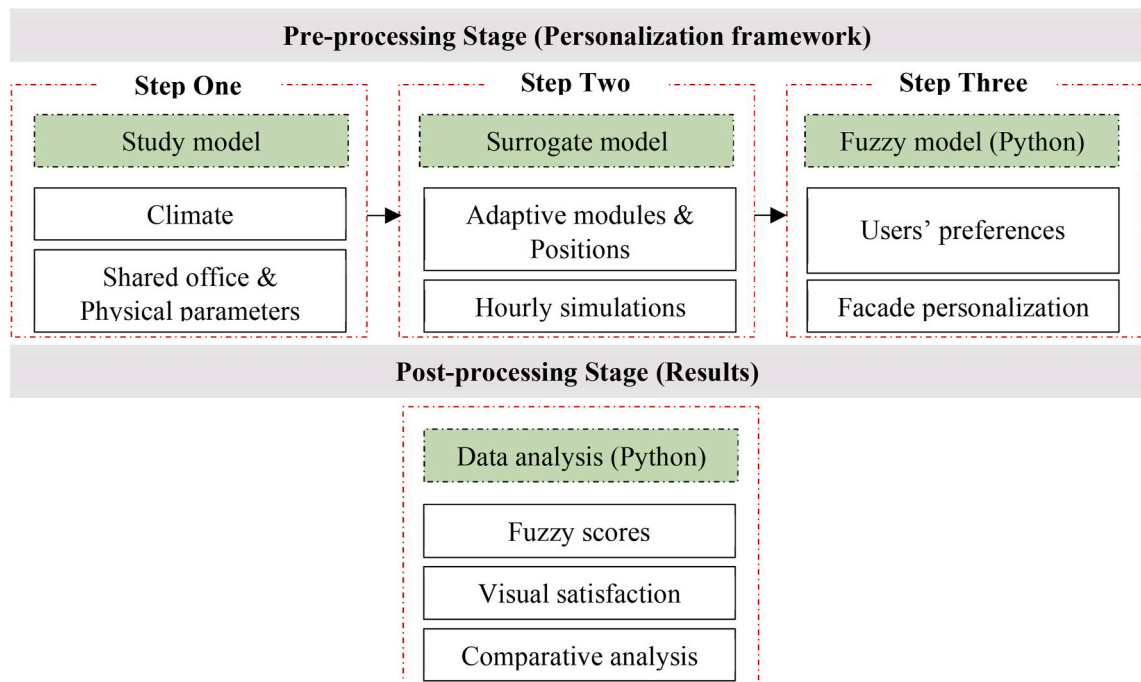

Fig. 1. The personalization framework.

- To develop an integrated control programming to find the optimum façade personalization with respect to the users' visual comfort performance on a timely manner;
- To compare the façade personalization performance against typical automated shading controls.

The main novelties lie within the methodological framework of this research that (1) simultaneously considers the visual comfort condition and desires of two occupants in a shared office space, (2) utilizes Fuzzy logic to consider the uncertainties between the delivered façade adaptation and users' preferences, and (3) evaluates the personalization impact of a modular adaptive façade design on users' visual satisfaction.

2. Personalization framework

To implement personalized control, the façade elements should be controlled through a decentralized mechanism where both conventional shading systems like Venetian blinds and modular façades could be controlled whether in form of sections [44] or individually [44,45]. In this research, the personalization framework includes two main steps as illustrated in Fig. 1: 1) pre-processing stage where the hourly simulations are exercised for a test cell as inputs for the fuzzy model to optimize the modules' personalization based on the users' preferences, and 2) post-processing stage to represent the personalized modules along with their corresponding final fuzzy scores and users' visual satisfaction as the main results. Accordingly, each stage will be explained in the following sub-sections.

2.1. Study model

The reference model is a north-faced office space with a modular adaptive façade in Melbourne, Australia. The dimensions of the space are 4.4 m width, 8.0 m depth, and 3.4 m height, as shown in Fig. 2. The office is assumed to be located on level 10th to benefit view from the entire façade which is divided into 12 square modules with the dimension of 1 m × 1 m, in form of 3 rows and 4 columns. Each module can be in one of the four "fully closed", "fully open", and two "intermediate" states as depicted in Fig. 3 which the original concept is derived from an origami-based design and can be adapted in hundreds of possibilities, but for the purpose of this research,
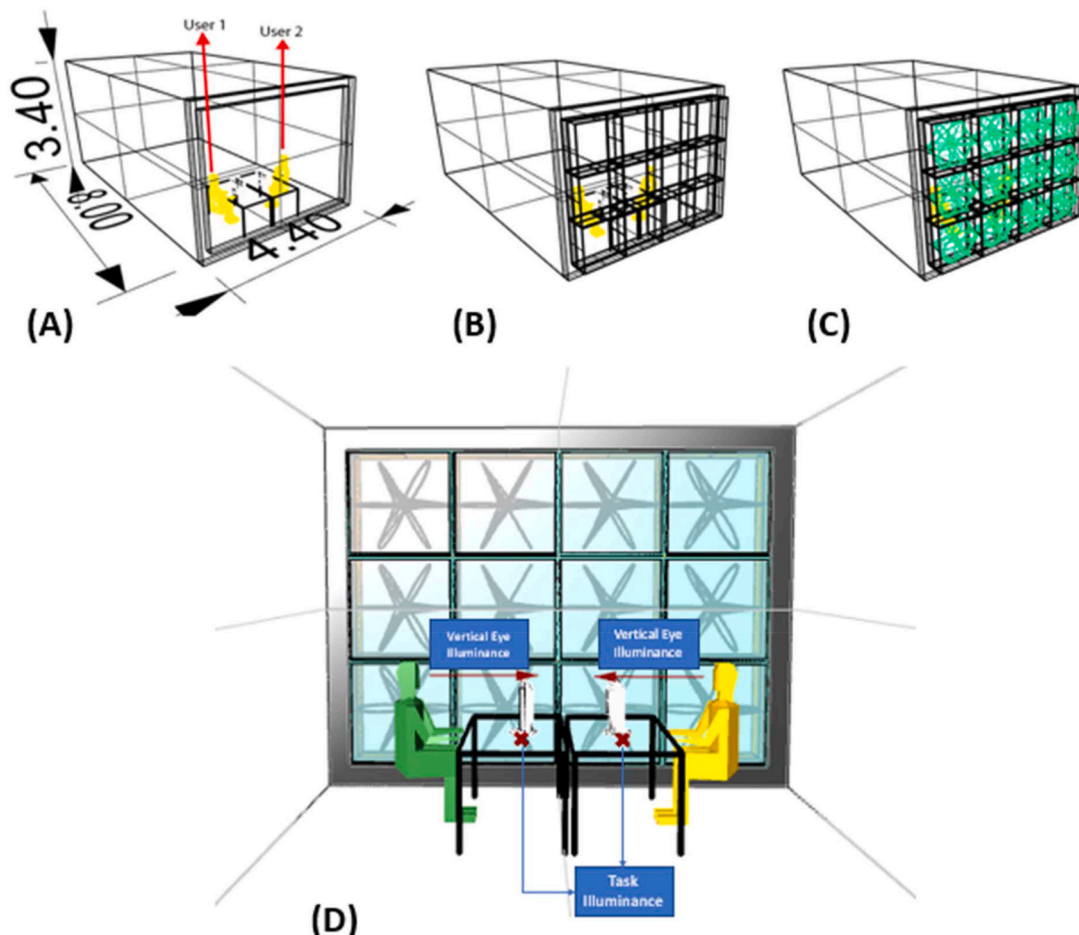

Fig. 2. (A) The reference shared office space, (B) structural frame of the façade, (C) the modular adaptive façade, and (D) Sensors used in the simulations.

four of the states were selected [50]. The daylight simulation parameters including the internal finishes' reflectance and are reported in Table 1. Two occupants in a sitting position are assumed to be located at their tables at an equal distance of 1 m from the window. The 3D modelling is performed in Rhinoceros program and daylight simulations are done using Ladybug-tools (LBT) in Grasshopper. LBT are open-source plugins that incorporate RADIANCE and DAYSIM engines to simulate the daylight and glare environment, numerically, with reliable accuracy.

2.2. Surrogate model

The modular adaptive façade shown in Fig. 1 contains 12 controllable modules, each having four possible states that result in 4 powered by 12 (approximately 16.8 million) individual simulations considering any single possible combination of the modules. Assuming an average daylight simulation time of 3 s for each façade configuration requires 195 days to finish the task which is a highly time-consuming process and not practicable. Thereby, to make the simulation procedure feasible, a linear surrogate model is used to narrow down the total number of required simulations to the multiplication of the number of modules by the number of each module state. This means only 48 single simulations are conducted as representatives of 4 states for all 12 modules. It should be noted that the proposed surrogate modelling approach has been validated previously by Ref. [49].

For the façade module personalization purpose, three visual comfort metrics including vertical eye illuminance (E_V), task illuminance (E_V), and view to outdoor (VR) are considered as the main user comfort objectives and potential drivers to interact with the façade. However, among these metrics, only E_V and E_T are climate-dependent, while VR is calculated based on the occlusion rate on the windows depending on the façade module states. Following the surrogate model, hourly simulations for an entire year (8760 h) of one module configuration are done through LBT to obtain E_V and E_T for each module state and repeated. However, based on the proposed surrogate model method, except for the intended module, all the other façade modules are considered as black surfaces with no daylight penetration (Fig. 3) where the overall glare risk (E_V) and daylight level (E_T) of each façade configuration are assumed as the sum of E_V and E_T for each module of the given state (Fig. 4), respectively (equations (1) and (2)).

Alternatively, to calculate the view ratio for each user, the façade modules are divided into two vertical portions that every six modules will be adjusted to the corresponding user based on the preference through an averaged VR value of each portion (Fig. 5, B). This is mainly because the case study is located above the ground and the entire façade could facilitate view to outdoors, while the division allows finer resolution of personalization for a shared space. The averaged VR is associated with individual module positions where fully-open, fully-closed, and intermediate positions provide 93.3%, 34.5%, and 86.5% unconcluded view to outdoors (Fig. 5, A). It should be noted the occlusion rate calculation is based on the grid method used by Refs. [51,52]. Ultimately, the hourly simulation results for E_V, E_T, and VR metrics are stored as.csv files as inputs to personalize the façade modules using the fuzzy logic in the next step.

$$E_{T,facade} = \sum_{i=1}^{12} E_{T,module\ (i)} \qquad\qquad (1)$$

$$E_{V,facade} = \sum_{i=1}^{12} E_{V,module\ (i)} \qquad\qquad (2)$$

2.3. Fuzzy model

To address the stochastic user behavior due to individual characteristics and demographic, the range of users' visual preferences are randomly generated within a specific range as presented in Table 2 for every hour to feed into the proposed control algorithm. The two different preference ranges without any overlapping conditions for each metric are selected to emulate two occupants with different and conflicting preferences as the worst-case scenario, while the random selection is a representation of the occupant's stochastic visual comfort preference throughout working hours and to enhance the façade responses to occupants' moods [53]. Thus, the values are then used in equations (3)–(5) to assure the occupant-centric adaptation of the façade modules. In addition, the ranges of the users' visual preferences are specified in a way that they do not exceed the E_V and do not fall short of E_T recommended thresholds according to [[14,54]]. It should be noted that these ranges are only used as indications of two different users, thus in practice, these numbers
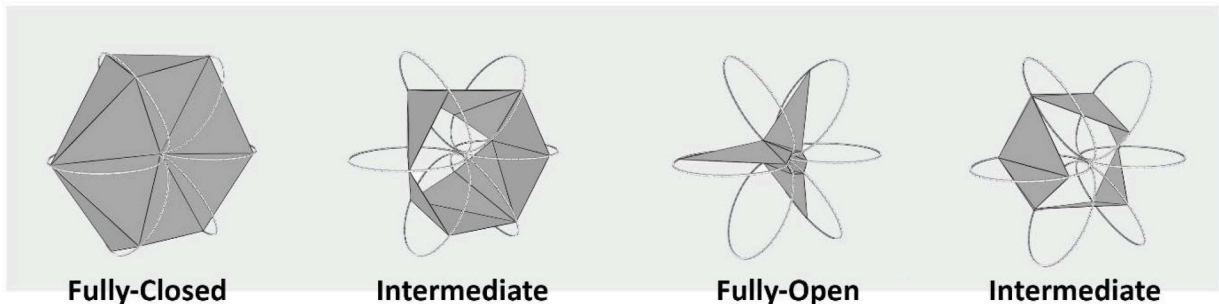

Fig. 3. Façade module states.

Table 1

Daylight simulation parameters.

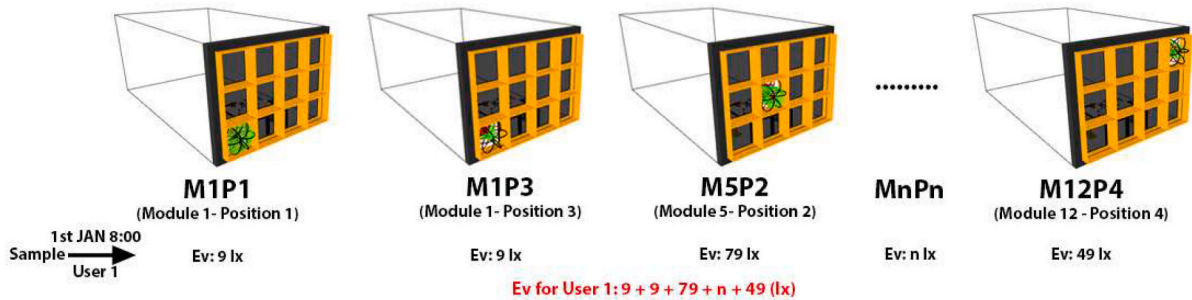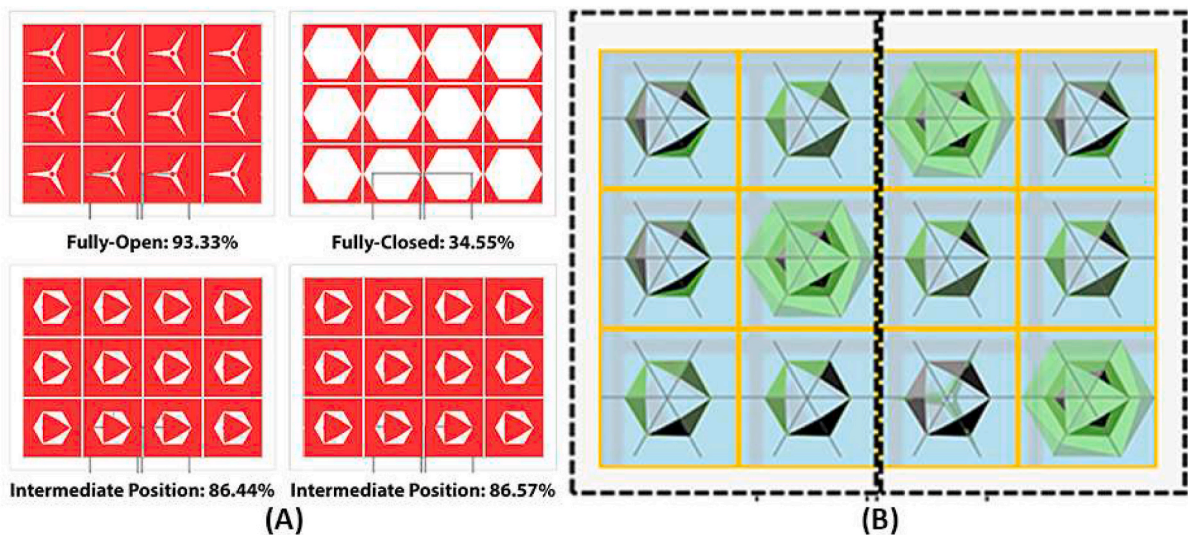| Parameter	Value
Location	Melbourne, Australia
Window visible transmittance	85%
Internal wall reflectance	40%
Ceiling reflectance	80%
Floor reflectance	20%
Furniture reflectance	10%
Modular shades reflectance	85%
ab (Ambient Bounces)	6

Fig. 4. Surrogate modelling approach.

Fig. 5. View to outdoors calculation method.

could be derived from surveys or questionaries. Moreover, in this research, the prioritization order to personalize the façade modules is given to E_V, E_T, and VR, respectively, followed by the previous study [42].

The fuzzy logic is coupled with a control framework depicted in Fig. 6. During working hours excluding weekends, users' visual preferences in terms of E_V, E_T, and VR are generated within the domains for each user as the inputs (Table 2) on an hourly basis in which the aim is to find the best façade configuration to satisfy both users' visual comfort demands. Initially, this is done by a random search process among hourly pre-simulated datasets (stored.csv files) to find the best fuzzy score, and if it was unsuccessful, then a genetic algorithm will be applied to derive the highest fuzzy score with respect to the occupants' visual satisfaction. Alternatively, during weekends, the façade modules' personalization will no longer seek the users' visual performance, but instead, monitoring the seasonal solar gain is the main driver. Thus, the façade modules are either "fully closed" in wintertime, or "fully open" in the summertime and shoulder seasons. This process will be repeated on an hourly basis to calculate users' visual satisfaction using fuzzy logic and optimize users' visual satisfaction by finding the optimal combination of the façade module states in a timely manner.

In particular, fuzzy logic is an approach representing "degrees of truth" rather than the "true/false" Boolean logic (crisp logic) and

Table 2

Users' visual preference ranges.

$$E_{T,facade} \geq E_{T,user} \qquad (3)$$

$$E_{V,facade} \leq E_{V,user} \qquad (4)$$

$$VR_{facade} \geq VR_{user} \qquad (5)$$

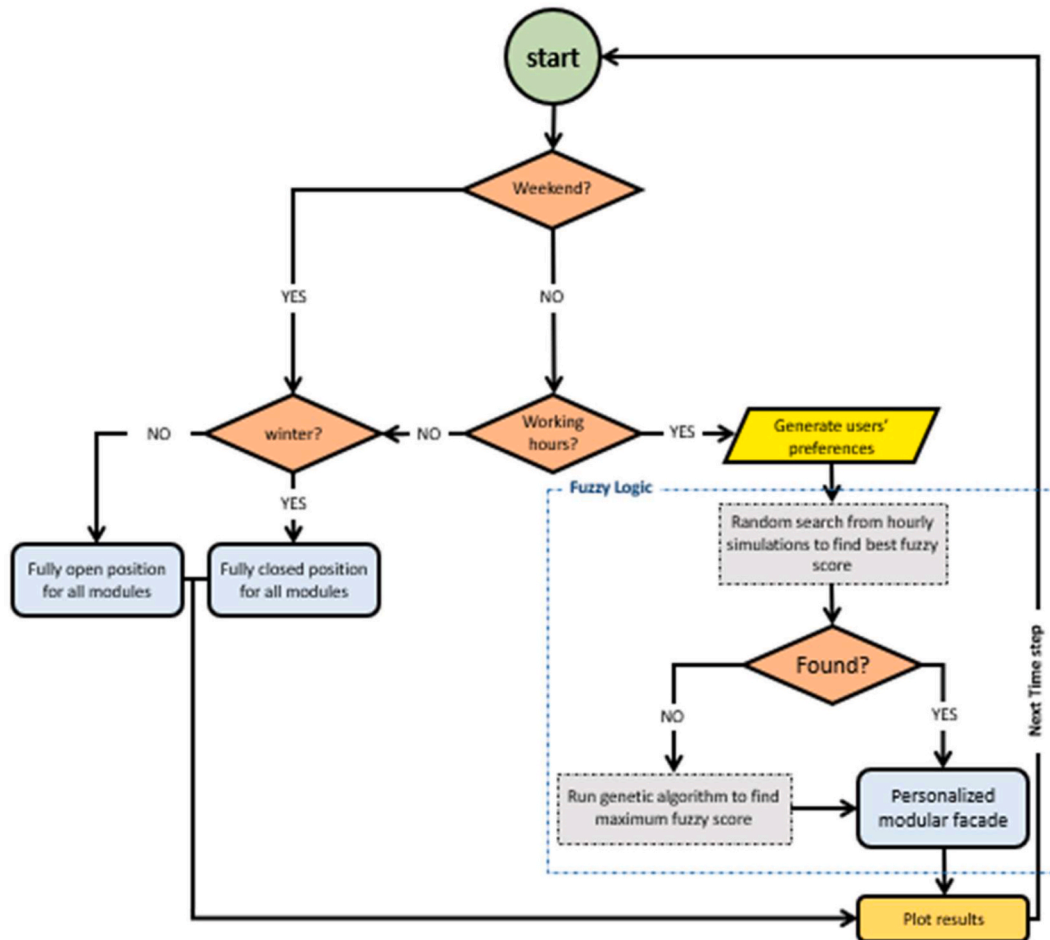| Metrics	User 1	User 2
E_V (lx)	4200–4760	3000–3500
E_T (lx)	850–950	300–600
VR	0.6–0.8	0.3–0.5

Fig. 6. The developed flowchart to personalize adaptive façade module.

has a wide application in controlling strategies with the aim of providing comfort in buildings [55,56], or developing new metrics based on comfort responses [57]. Using the fuzzy method in the current study helped to calculate the users' visual satisfaction encompasses within four steps through Python programming language: (1) specification of the users' visual preferences and addressing the uncertainties to construct a membership function (MF), (2) metrics fuzzification (i.e., task illuminance, vertical eye illuminance, and view to outdoor), (3) rules operation and output calculation, and (4) defuzzification and users' visual satisfaction evaluation.

Membership functions are an integral part of the personalization strategy of the façade modules to accurately imitate the occupants' reasoning, considering the module states can provide acceptable visual comfort conditions to some degree, rather than recognizing them as unacceptable entirely (e.g., a binary condition). This capability offers a great opportunity in cases where there might be conflicts between two or multiple variables (e.g., discomfort glare for 1st user vs. view to outdoors for the 2nd user). This means a little variation in the three objectives with respect to the users' preferences is still acceptable which is an opportunity given by

the fuzzy logic. For example, considering E_T and VR values delivered by the façade personalization near to the occupants' preferred values as unacceptable conditions dictates utilizing a crisp logic as opposed to fuzzy logic. In other words, when the user's visual preference is E_V 4300 lx, E_T 900 lx, and VR 0.7, and the personalized façade condition with a combination of module states results in E_V, E_T, and VR of 4450 lx, 840 lx, and 0.67, respectively, the crisp logic evaluates the condition as unacceptable while in the fuzzy logic is taken as acceptable with the possibility of 0.7, 0.6, and 0.9 for E_V, E_T, and VR, respectively (Fig. 7). This feature adds a significant value to simulate the uncertainty of occupants' visual satisfaction to enhance the façade personalization performance.

To that end, MFs are responsible to calculate the uncertain level and its impact on users' visual satisfaction score. In this research, a form of Trapezoid MFs is applied which is a four-coordinate-based method [58]. Four points' coordinates are required to build a membership function to identify the satisfaction and dissatisfaction rate of the two occupants in the space. Each point represents the magnitude level from visual comfort to discomfort level (Table 3). In the case of E_V, acceptable MF considers the absolute glare-free condition when E_V is equal to 0 as the first two points towards the user preference threshold (point 3). Then, the maximum user tolerance is represented as point 4 when E_V is 600lux and 1000lux above the preference values for 1st and 2nd user, respectively. This consideration identifies absolute dissatisfaction feeling when the E_V level exceeds the maximum values (point 4). On contrary, unacceptable MF starts from user preference as a minimum value (point 1), and maximum user tolerance as point 2 while two times of user preference is considered as excessive glare risk, namely, intolerable condition (points 3 and 4). In the case of E_T, the acceptable MF considers the minimum task illuminance (100lx and 50lx less than the users' preferences) partially acceptable (point 1), while above their preferences is acceptable (points 2–4). On another front, the unacceptable MF for E_T starts from 0lx which represents an absolute dark space (points 1–2) towards slightly below the user preference (point 3) and meets the user preference (point 4). A similar method to E_T membership functions is applied for VR in which a value of 0.1 below the users' preferences is considered as a maximum allowable threshold.

After the fuzzification process, a set of IF/THEN rules imposing on the intended visual metrics are specified to determine the fuzzy scores. In this research, the final fuzzy score represents both users combined visual satisfaction, or namely, the comfort score. To this end, each visual comfort metric can take two acceptable and unacceptable conditions which resulted in 64 rules to be exerted on the fuzzified inputs to calculate the comfort score which varies from 0 to 30. To calculate the comfort score, Gaussian membership function including 13 levels where M1 occurs when all of the inputs (i.e. $E_{V1,facade}$, $E_{V2,facade}$, $E_{T1,facade}$, $VR1_{facade}$, $VR2_{facade}$) are unacceptable for both users and M13 occurs when all of the inputs are acceptable (Fig. 8). It should be noted that the prioritization level impacts the comfort score accordingly in which satisfying glare condition for both users impacts more than E_T on the comfort score and E_T has more effect than VR. Table 4 outlines seven examples of the specified rules. To determine the values of each rule through fuzzy logic,
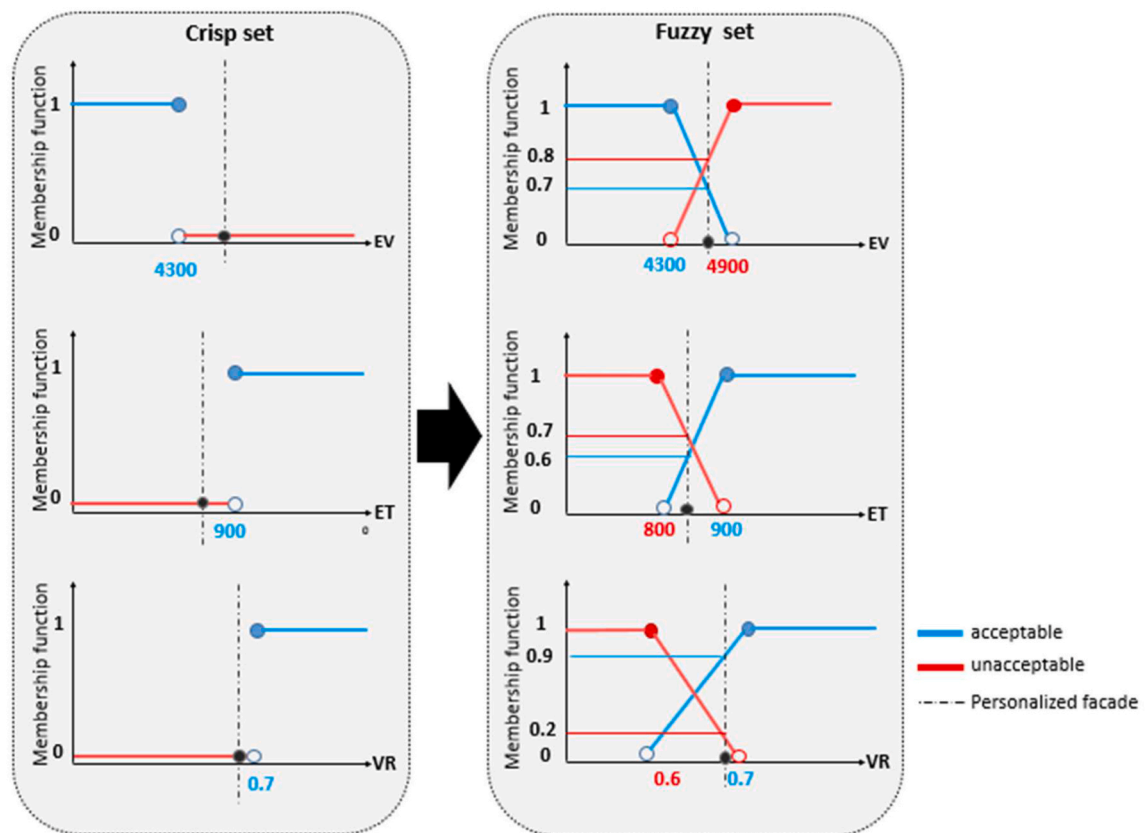

Fig. 7. Crisp logic and fuzzy logic difference.

Table 3

Trapezoid fuzzy membership function for acceptable and unacceptable conditions.

| Acceptable MF	$EV1_{MF}$	$ET1_{MF}$	$EV2_{MF}$	$ET2_{MF}$	$VR1_{MF}$	$VR2_{MF}$
Point1	0	$E_{T1,user}$-100	0	$E_{T2,user}$-50	$VR1_{user}$-0.1	$VR2_{user}$-0.1
Point2	0	$E_{T1,user}$	0	$E_{T2,user}$	$VR1_{user}$	$VR2_{user}$
Point3	$E_{V1,user}$	$2* E_{T1,user}$	$E_{V2,user}$	$2* E_{T2,user}$	0.9	0.9
Point4	$E_{V1,user}$ +600	$2* E_{T1,user}$	$E_{V2,user}$ +1000	$2* E_{T2,user}$	0.9	0.9
Unacceptable MF	$EV1_{MF}$	$ET1_{MF}$	$EV2_{MF}$	$ET2_{MF}$	$VR1_{MF}$	$VR2_{MF}$
Point1	$E_{V1,user}$	0	$E_{V2,user}$	0	0	0
Point2	$E_{V1,user}$ +600	0	$E_{V2,user}$ +1000	0	0	0
Point3	$2* E_{V1,user}$	$E_{T1,user}$-100	$2* E_{V2,user}$	$E_{T2,user}$-50	$VR1_{user}$-0.1	$VR2_{user}$-0.1
Point4	$2* E_{V1,user}$	$E_{T1,user}$	$2* E_{V2,user}$	$E_{T2,user}$	$VR1_{user}$	$VR2_{user}$
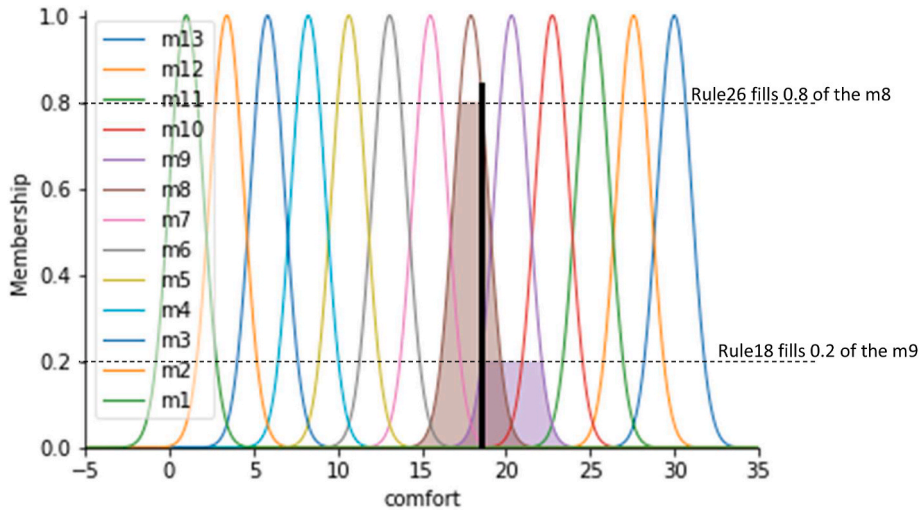
Fig. 8. Example of defuzzification process.

the standard operator 'AND' is used to obtain the common acceptable value across the metrics (Table 4). In this example, Rule32 and Rule24 resulted in the "middle" and "high_middle" comfort ranges (Table 4).

Finally, to indicate the exact comfort score, the defuzzification process is applied through the centroid method (center of gravity). However, the fuzzy output, which ranges from 0 to 1, should be converted to a score from 0 to 30 to evaluate the comfort score. Fig. 8 shows an example of a single simulation derived from Rule18 and Rule26 and its position within the defuzzification process represented by a black line as the final score of 18.5.

2.4. Optimization

At the initial stages, the random search in data is selected to find the optimal state of façade modules with maximum comfort score. This is mainly because as opposed to typical optimization workflows that read the entire alternatives which are time-consuming in large datasets, the random selection facilitates finding the optimal module states in noticeably less time. Nonetheless, if the random search process could not lead to the optimal state, the maximum value of the users' visual satisfaction score will be derived from genetic algorithm optimization.

Each module at a certain position out of four possibilities resulted in varying E_V and E_T values depending on the climate using the surrogate model in which the entire 8760 simulations were stored in form of.csv files (Fig. 4). Random selection searches the hourly results among different module positions containing 48 rows of data that each represents a module with the certain position for each visual comfort indicator (E_{V1}, E_{V2}, E_{T1}, E_{T2}, VR_1, and VR_2) (Fig. 9). After randomizing the modules' positions on an hourly basis, a dataset with 12 rows is constructed that every row illustrates the adjusted modules individually and their impact on the corresponding fuzzy score which represents the overall users' visual satisfaction in a shared space. This process continues to find a combination of modules' state that could result in the highest fuzzy score of 30 but is limited to 500 iterations.

However, if the random searching process fails to find the optimum modules positions, the genetic algorithm as the alternative method would take the responsibility of trying to reach the highest users' visual satisfaction. Nonetheless, if the fuzzy score of a configuration was found to be less than that of fully open position for all modules, the algorithm will adjust them all in a fully open position to maintain a sufficient view to outdoors and task illuminance. Noting that this is only applied when the genetic algorithm fails to find the optimum solution. In addition, the genetic algorithm's hyperparameters are as follows:

Table 4

Examples of rules and their corresponding outputs.

Rules	Input						Output
	$EV1_{facade}$	$EV2_{facade}$	$ET1_{facade}$	$ET2_{facade}$	$VR1_{facade}$	$VR2_{facade}$	$comfort_{total}$
Rule1							Very_high (m13)
Rule10							High (m11)
Rule24							High_middle (m8)
Rule32							Middle (m7)
Rule41							Middle_low (m6)
Rule59							Low (m3)
Rule62							Very_low (m1)

Blue**: Acceptable, Red: Unacceptable**

Rule32 MINIMUM [EV1 (unacceptable)=1 & EV2 (acceptable)=1 & ET1 (acceptable)=1 & ET2 (acceptable)=1 & VR1 (acceptable)=1 & VR2 (unacceptable)=0.85] = 0.85

Rule24 MINIMUM [EV1 (unacceptable)=1 & EV2 (acceptable)=1 & ET1 (acceptable)=1 & ET2 (acceptable)=1 & VR1 (acceptable)=1 & VR2 (acceptable)=0.7] = 0.7
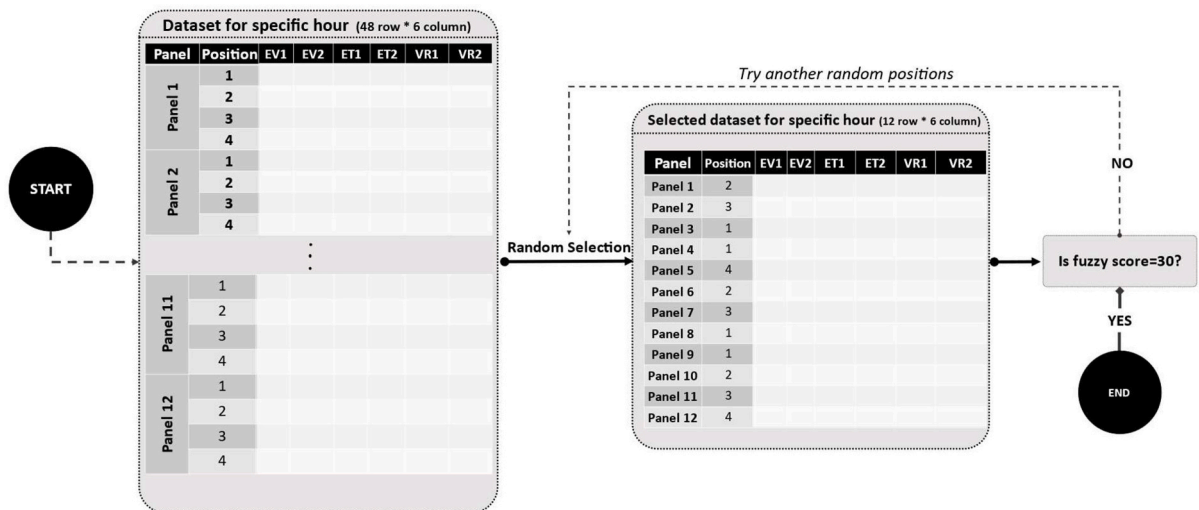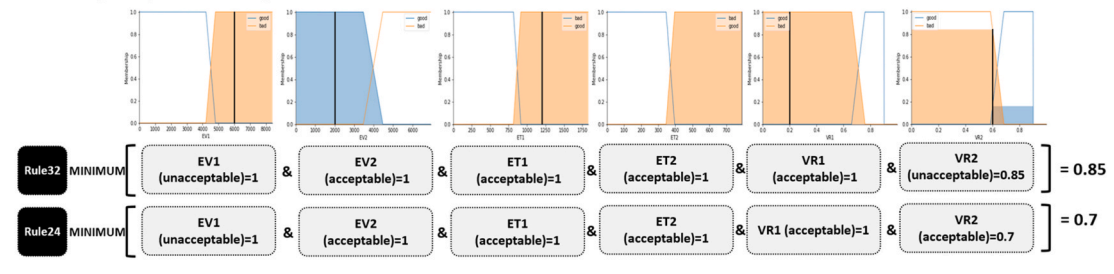

Fig. 9. Random searching process to find the optimal modules positions.

- **Mutation probability** is basically a measure of the likeness that random elements of the chromosome will be flipped into something else (set as 0.2).
- **Elite ratio** is the proportion of the number of elites to the total population size (set as 0.01).
- **Crossover probability** is the probability that crossover will occur at a particular mating (set as 0.5).
- **Parents portion** is the portion of the population which mate and recombine to create off-springs for the next generation (set as 0.3).
- **Crossover type** is a genetic operator used to combine the genetic information of two parents to generate new off-spring (set as two-point).
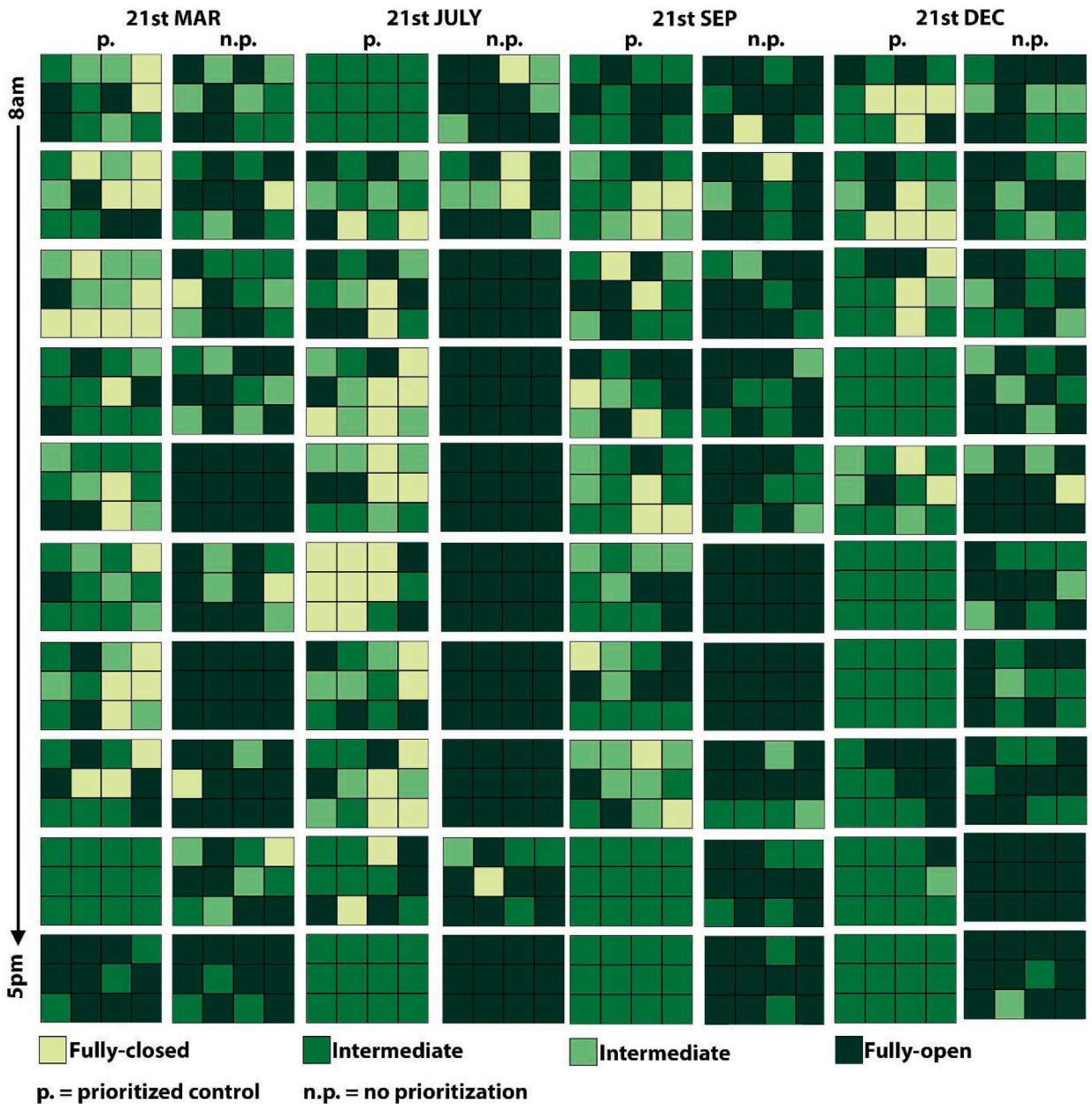
Fig. 10. Optimal façade configuration based on 'prioritzied control' and 'no prirotization' scenarios.

3. Results

Following the optimization process, the values of the three intended visual metrics in this study (i.e., vertical eye illuminance, task illuminance, and view to outdoors) are analyzed in two different time resolutions on an hourly basis. The first resolution is based on the 21st day of the four representative months of March, July, September, and December (daily results), and the second one is based on the third week of each of these four months (weekly results). The daily results are illustrated in section 3.1 based on the personalization impact of the modules' states, while the weekly results are presented and analyzed in sections 3.2 to 3.4. As discussed earlier, users' visual preferences are specified randomly representing a stochastic behavior and considered to be different between two users to imitate the real condition more accurately in a shared space. The ranges of the occupants' visual preferences are brought in Table 2 for the three investigated metrics. Accordingly, the hourly preferred values are determined for E_V tolerance and E_T and VR preferences for each of the two users in the shared office space. The developed framework for the modular adaptive façade personalizes the façade configuration based on the users' visual comfort preferences to improve their satisfaction, or in other words, increase the fuzzy score. Ultimately, to rate the optimal solution, a scoreboard is given in section 3.5 presenting the performance of the proposed framework as
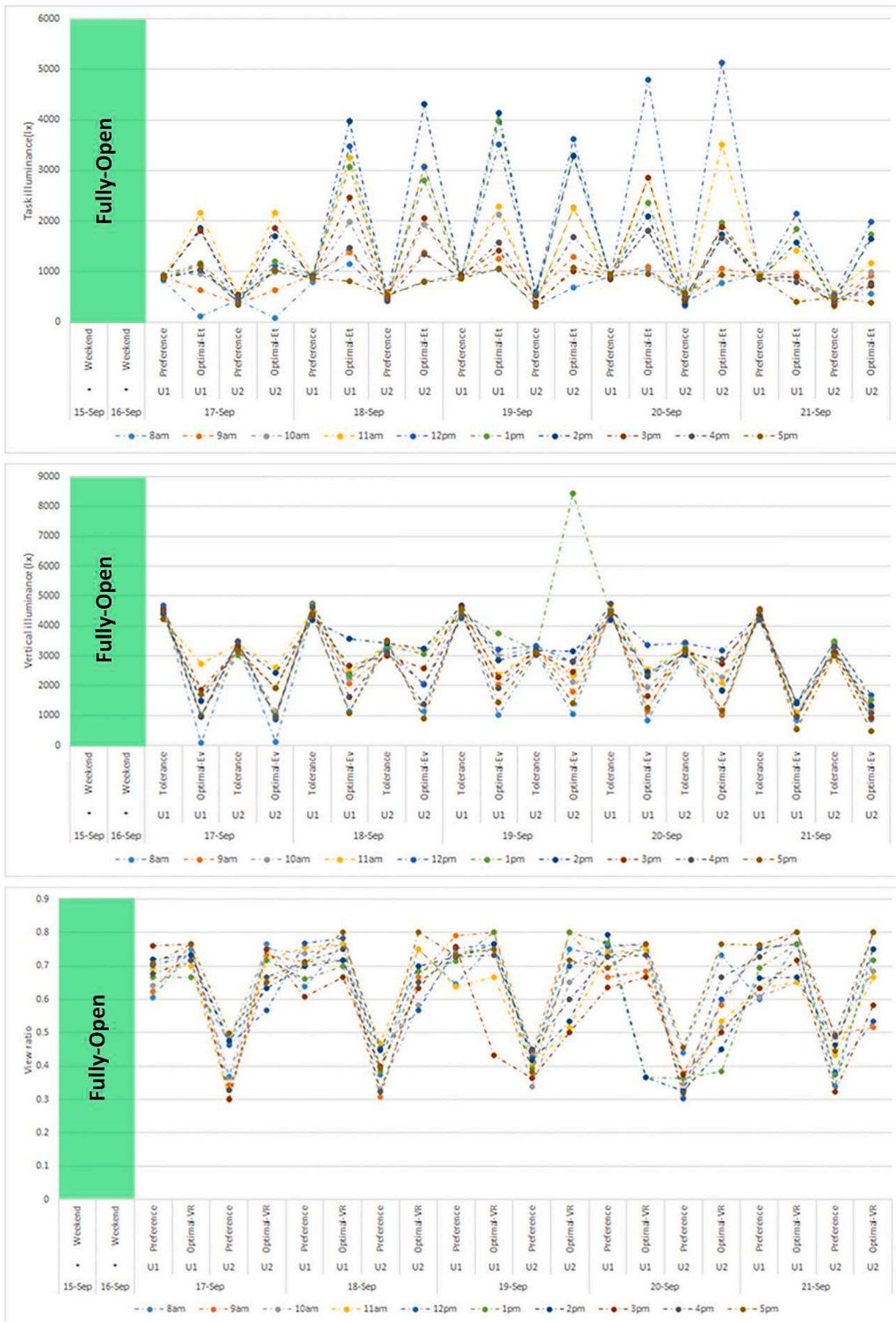
Fig. 11. Visual comfort performance on September 15th- 21st (spring week).

opposed to a baseline condition.

3.1. Personalization impact on façade configuration

The optimal state of the modular adaptive façade is specified for the 21st of March, July, September, and December from 8am to 5pm in an hourly time step based on two scenarios: 1) when the personalized control prioritization order is glare, task illuminance and view to outdoors, and 2) when there is no prioritization, and three visual comfort indicators have equal weight. These optimal states are determined based on the fuzzy score, which simultaneously encompasses both users' visual satisfaction in terms of three metrics including E_V, E_T, and view to outdoors.

As it is illustrated in Fig. 10, in the case of 'no prioritization' scenario, the optimal configuration of the modular façade is obtained when all modules are fully-open at the most working hours (7 out of 10) of the July 21st (wintertime), whereas the fully-open state of all modules leads to the optimal façade configuration in only 1 h of the December 21st (summertime). Despite the fact that in wintertime solar altitude is at its lower level but keeping fully-open modules could achieve the highest score among other positions but could cause glare for both users. On the other hand, higher solar altitude in the summertime and potential discomfort glare due to inner reflection caused a more personalized response on the façade's modules and accordingly making the fully-open state of all modules less probable during the evaluated hours in a way that vertical eye illuminance would not exceed the E_V tolerance values of both users. On the 21st of March and September, the fully-open state of all modules is found to be the optimal façade configuration in the middle hours of the working day when the solar altitude angle is suitable to prevent unwanted values of E_V causing glare problems for both users while providing preferred values of E_T and view to outdoors. During the early working hours of all four analyzed days, the occurrence of the intermediate and fully-closed states of the modules is more likely due to the relatively low solar altitude; meanwhile, a number of modules are still kept fully-open to satisfy view to outdoors. On 21st day from March to December, a trend can be seen in the way that the façade modules tend to be in the intermediate and even fully-closed states on the spring representative day, while as we approach summertime, the optimal configuration of the façade is when the most modules are fully-open, but could not satisfy both occupants with respect to discomfort glare (section 3.4). Overall, the daily plots represent the necessity of the façade's single module personalization and its impact on finding the least glare probability with sufficient indoor daylight and view to outdoors for both occupants.

On another front, when the personalized control integrates the control prioritization within the algorithm, there is a significant change in module adjustments individually (Fig. 10). Firstly, the number of fully-closed positions across the façade modules has increased noticeably especially in the wintertime to block the glare as the 1st objective where at 1pm more than 50% of the modules are closed, while it might impact task illuminance and views negatively and will be discussed in the next section. Secondly, intermediate positions become an alternative solution to redirect daylight to indoors and prevent glare. For example, on 21st of December the majority of fully-open positions turned into either one of the intermediate positions. And lastly, the prioritization levels could increase the modules' uniformity in a few hours such as 4pm on 21st of March where the optimum configuration is found to be an intermediate position for all modules instead of altering each module differently. These findings confirm the personalization impact on providing different façade configurations depending on the control algorithm setup that adds a new area to investigate multiple control options, although this is not the scope of the current research.

3.2. Visual comfort performance

In this section, weekly results of the optimal façade configurations per each time step are plotted. Fig. 11 illustrates the representative spring week. In terms of vertical eye illuminance as the first control priority, the aim is to optimize the adaptive façade modules in a way that the hourly values of vertical eye illuminance will not exceed those of both users' tolerance. The 1st user is a more tolerant occupant with higher vertical eye illuminance tolerance (E_V range 4200–4760lx), whereas user number two tolerates fewer values (E_V range 3000–3500lx) for this metric. While the 2nd user is more sensitive to glare performance, the personalized façade modules could provide comfortable glare-free environments for both users during all working hours except 1 h for the 2nd user (1pm on 19th September) which is mainly due to the given highest priority within the control. A relatively similar trend can be seen in the other mid-season representative week (Fig. 13) and only the second user is not satisfied at 10am and 4pm which emphasizes the negligible impact of user view direction on glare performance. In the contrary, sun altitude distinguishes the control performance in summer and winter weeks. During summer, the personalized control could mitigate the discomfort glare for both users throughout the hours (Fig. 12), while in winter week the 2nd user could experience intolerable glare frequently at 1pm frequently (Fig. 14). Therefore, controlling glare for the 2nd user at 1pm found to be the most challenging decision as opposed to 8am when the direct and diffuse solar radiation are at lowest levels. These observations indicate the successful personalized control application in all representative weeks by controlling glare as the first priority in which 1) there is no single hour for the 1st user to experience intolerable glare, and 2) the 2nd user experiences glare only during less than 4% of the occupied hours. Moreover, the E_V values corresponding to the optimal façade configuration at the last two working hours lean toward zero due to sunset hours. It should be also mentioned that the façade modules are considered to be a fully-closed state during the weekend hours of summer and a fully-open state during those non-summer seasons.

As the 2nd control priority objective, the 1st user prefers higher E_T values (E_T range 850–950lx), whereas the 2nd user desires lower daylight (E_T range 300–600lx). The optimal façade configuration attempts to visually satisfy both users in terms of E_T while taking two other metrics (i.e., E_V and VR) into account as well. In all representative weeks, the personalized control couldn't provide sufficient indoor task illuminance for both users early in the morning (8am) due to sun position and lower global horizontal illuminance. A similar trend could be seen in the late afternoon at 4pm and 5pm especially in summer week (Fig. 12) because of a uniform module adjustment in the intermediate position to satisfy the glare performance (Fig. 10). A common finding with respect to time frames is that the proposed control could significantly increase the task illuminance from 11am to 2pm in all weeks and in some cases, it reaches up to 3000lx (e.g., Fig. 13) difference comparing with the user preference without any potential glare risks which suggests the
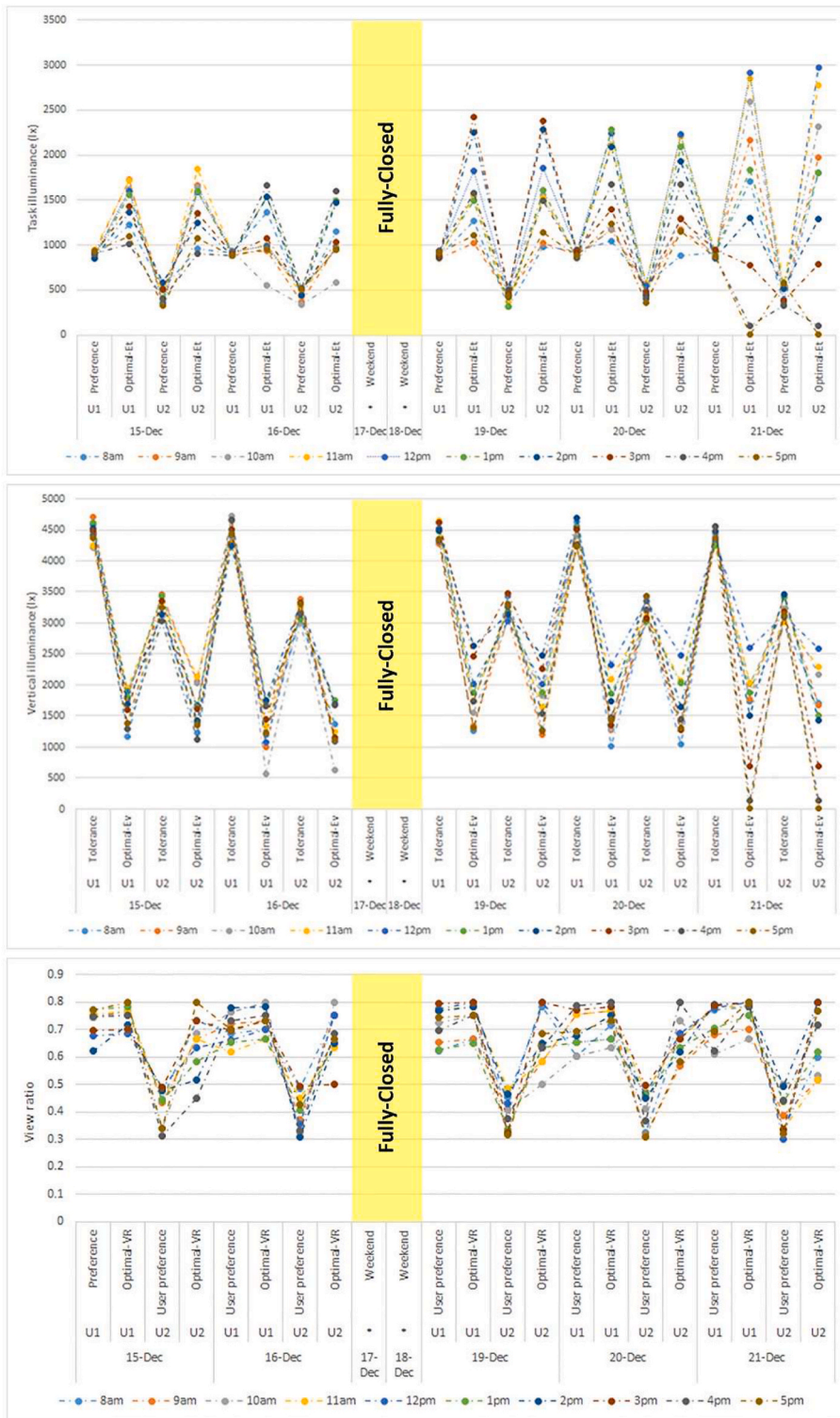
Fig. 12. Visual comfort performance on December 15th- 21st (summer week).
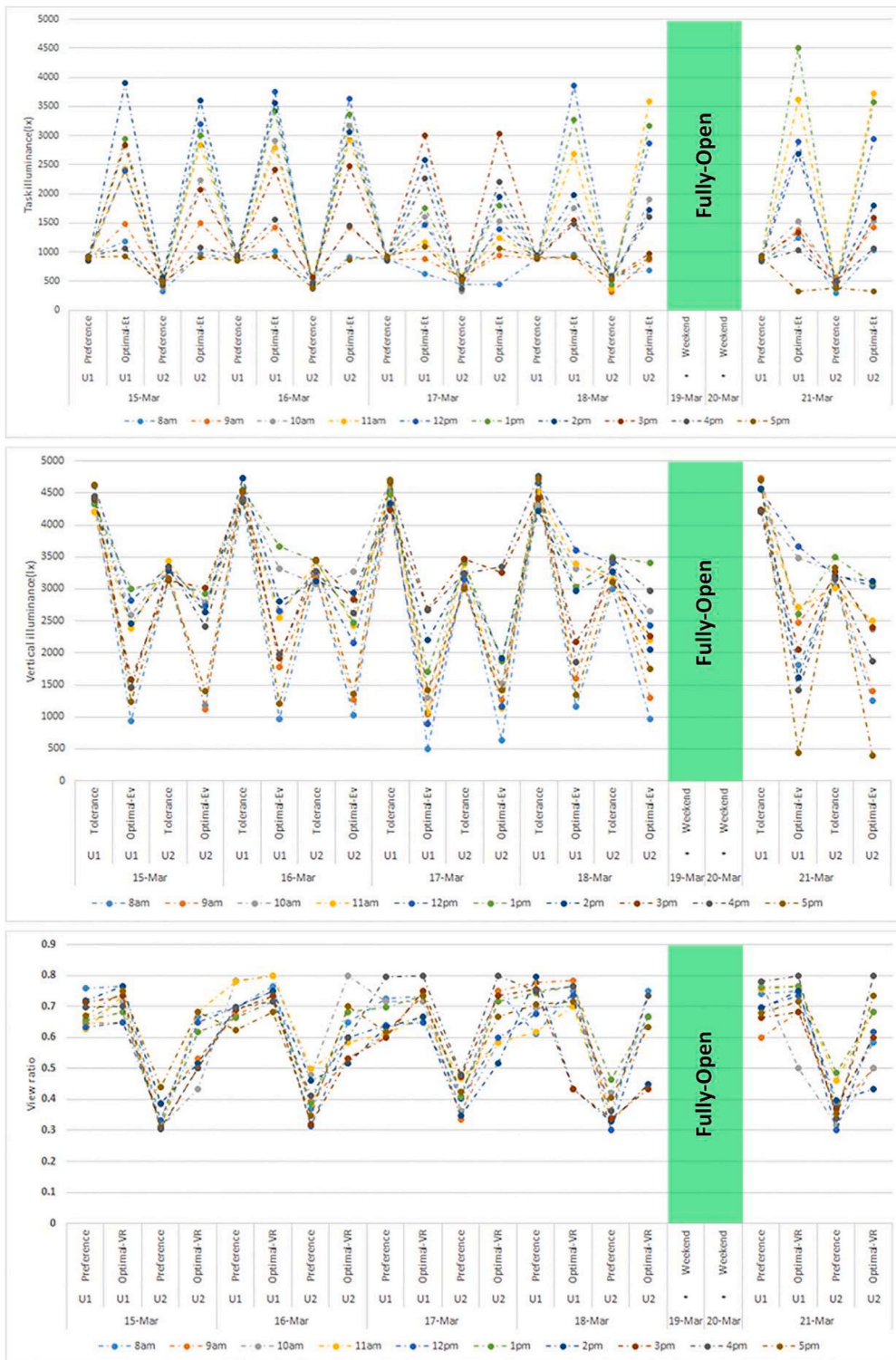
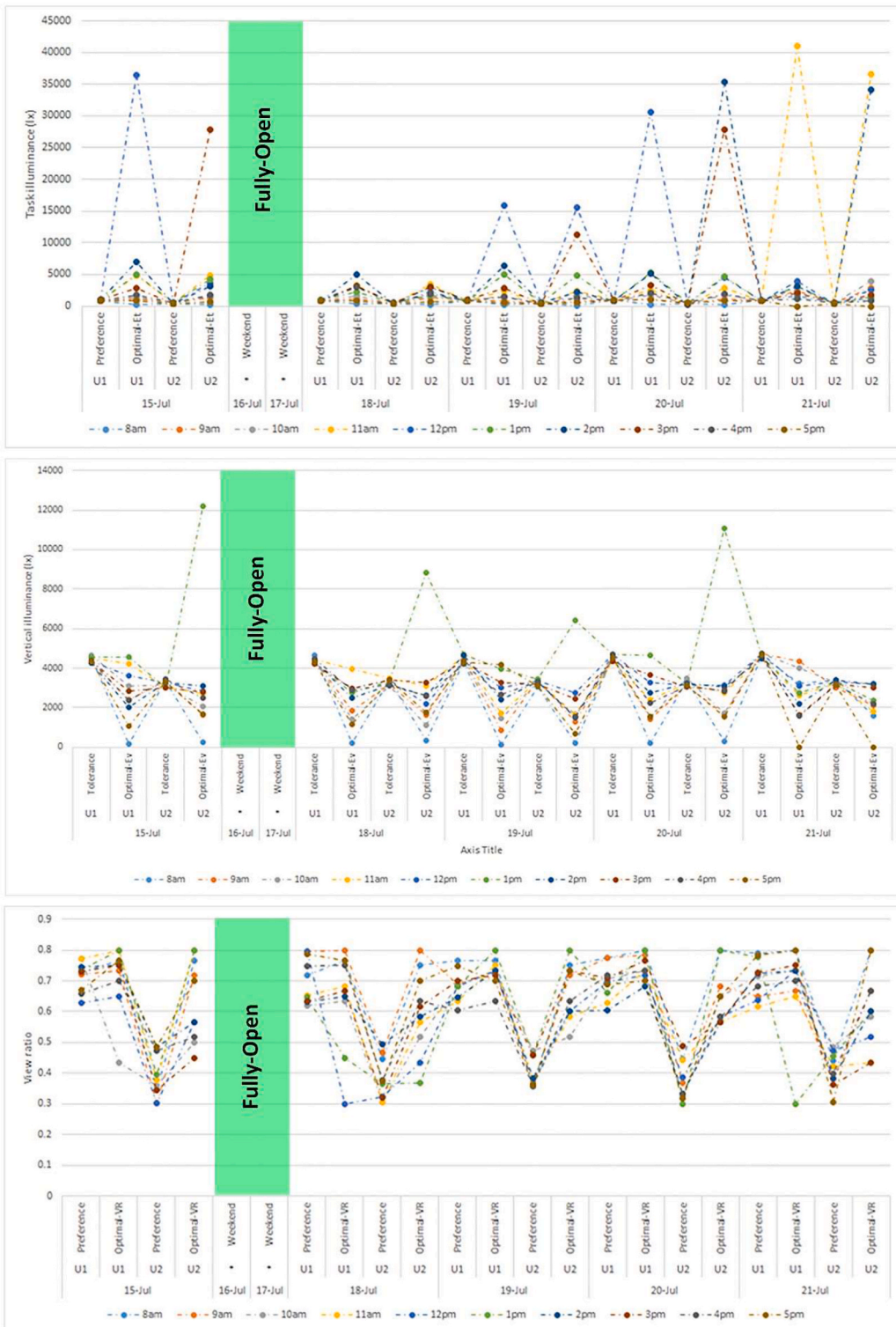**Fig. 13.** Visual comfort performance on March 15th- 21st (autumn week).

Fig. 14. Visual comfort performance on July 15th- 21st (Winter week).

prioritization benefit within the deployed algorithm. On another front, there are fewer improvements up to 500lx at early in the mornings and late in the afternoons which is due to the sun's position and angle. Among all weeks, the highest indoor daylight levels refer to the wintertime where the task illuminance in a few hours reaches above 15000lx (Fig. 14) as a result of direct daylight penetration through module gaps on the task planes while the glare performance criteria are met.

In order to control the view to outdoors as the 3rd priority, 1st user prefers higher view ratio values (in the range of 0.6–0.8), whereas user number two prefers fewer values for this metric (in the range of 0.3–0.5). The façade modules' personalization attempts to visually satisfy both users in terms of view ratio while maintaining acceptable E_V and E_T for both users. The results of this section show that both users are mostly satisfied in terms of view to outdoors during the entire working hours of the evaluated spring week (Fig. 11), except for 2pm (19th September) and 3pm (20th September) for the 1st user (Fig. 12). While in wintertime the sun inclination is low and the potential glare risk is higher, but the proposed control caused dissatisfaction for the 1st user during 8% of the time, whereas the dissatisfaction rate for the 2nd user comes to none, as shown in Fig. 14. Despite the counterbalancing antagonistic factors (more view, and less discomfort glare at view fields) as the main personalized control responsibility which could be even challenging in lower solar altitudes, observations confirm a significantly reduced number of dissatisfaction hours. Although VR is more sensitive to the users' location in the space and the specified facade portion for their views (Fig. 3), thus results can vary considerably between the two occupants.

Table 5 confirms that the average satisfaction percent during working hours of each visual comfort indicator is at least 83% related to the 1st user E_T performance who is facing West with higher daylight level preference, while the 2nd user is satisfied by 90%. In terms of E_V, even though the 2nd user could tolerate glare in a lower range, but the personalized façade modules offered a satisfaction level of 96.5% of the time as opposed to the 1st user with an absolute satisfaction rate with a higher tolerance threshold. This figure has impacted the view ratio in an opposite where the 2nd user experiences a 100% VR satisfaction rate, unlike the 1st user. This observation confirms higher tendency to close the façade modules on the left portion (according to Fig. 4) where there is a challenge to block the glare risk during late afternoons for the 1st user who is facing West. Focusing on the users' view direction and position, there is no significant difference between the users' visual satisfaction. User 1 and User 2 are satisfied by 92.5% and 95.5% in average which means the developed personalization framework could address different visual preferences in a shared space successfully without prioritizing one user's desires over another.

3.3. Performance comparative analysis

To evaluate the performance of the personalized control, two commonly used automated Venetian blind controls are selected as reference cases (Table 6). The first scenario (S1) takes the incident solar radiation on the window as the control trigger to adjust the Venetian blinds. This is basically an open-loop controller where there is no feedback loop from indoors to the controller. Unlike S1, the second scenario employs a closed-loop mechanism where the task illuminance on the desk drives the slat angles in three different positions as stated in Table 7. For the sake of comparative analysis, two considerations are made: 1) user preferences are kept identical to avoid any performance uncertainty, and 2) view ratio to outdoors in the case of Venetian blinds are considered by 0%, 45%, and 95% for fully-closed, semi-closed, and fully-open slat angles.

Fig. 15 compares the comfort score of the developed personalized control with the automated Venetian blind scenarios. In summer week, the personalized control could offer the highest possible score which means visual comfort was guaranteed for both users with few exceptions on December 21st where the comfort score dropped to 20 lower than S1 and S2 during the late afternoon. This means one of the visual comfort metrics, E_T followed by Table 5 results, could not be met for one or both users. Although in some cases, there is a significant comfort score difference (e.g., December 16th) between the modular façade and Venetian blinds controls by up to 20 points. During mid-seasons, the personalized control follows a similar trend, but still outperforms the automated Venetian blinds by 10 points most of the time. This observation confirms the incapability of the automated control scenarios to satisfy visual comfort metrics simultaneously for both users (Fig. 15). In the contrary, there is a remaining challenge in the wintertime to satisfy user's visual comfort preferences in wintertime when the sun position could potentially increase the glare risk which resulted in frequent 20-point comfort scores for personalized and automated controls, although modular façade personalization attempted to maintain the optimal comfort remarkably comparing with S1 and S2. In terms of performance quality, the personalization method over a modular facade could deliver consistent high-performance control throughout the weeks, unlike S1 and S2. However, employing a closed-loop control could perform better than an open-loop control mechanism which is in line with previous reviews [28], but taking one aspect of visual comfort (in this case, task illuminance) does not necessarily improve other aspects (glare and view to outdoors).

In addition, Table 8 highlights a statistical comparison to determine the positive effect of the personalized control system on visual comfort performance against the typical automated Venetian blind control scenarios. Since each control system performance does not follow a normal distribution sample, Wilcoxon test [60] as a non-parametric statistical hypothesis test is implemented to evaluate the

Table 5
Satisfaction occurrences from 8am to 5pm of the working days.

	User 1 - E_V (→)	User 2 - E_V (←)	User 1 – E_T (→)	User 2 – E_T (←)	User 1 – VR (→)	User 2 – VR (←)
MAR	50	48	44	44	47	50
JULY	50	46	40	45	44	50
SEP	50	49	41	44	47	50
DEC	50	50	41	48	50	50
Averaged satisfaction percent	100%	96.5%	83%	90%	94%	100%

(→) Facing West, (←) Facing East.

Table 6
Venetian blinds properties.

Slat orientation	Horizontal
Slat width	0.05 m
Slat separation	0.07 m
Slat thickness	0.00025 m
Slat angle	Ranges from 0° (fully closed) to 90° (fully open)
Slat conductivity	221 W/mk
Back/front sides visible/beam reflectance	90%
Beam/diffuse transmittance	0
Distance to glass	0.035 m

Table 7
Automated Venetian blind controls (adopted from Ref. [59]).

Scenario	Variable	Position	Control logic
S1[a]	Solar incident radiation on window (W/m^2)	Outdoor (open-loop)	If solar incident is above 200w/m^2, then close the blinds, otherwise open the blinds
S2	Task illuminance (lx)	Indoor (closed-loop)	If task illuminance for both users is less than their stochastic hourly preferences, then open the blinds, If it is within the preference ranges, then open/close the blinds by 45°, Otherwise, close the blinds

[a] S1= (Beam to Beam Solar Transmittance × Surface Outside Face Beam Solar Incident Angle Cosine Value) + Surface Window Transmitted Diffuse Solar Radiation Rate.

difference significance with and without the personalized control in which a p-value lower than 0.05 indicates a significant different between the proposed and automated controls (Table 8).

4. Discussions

In a shared space, the greatest distinction lies between individuals' comfort demands corresponding to their local visual environment and can provide a fundamental basis for further personalized control of an adaptive façade. In this regard, hourly simulations were conducted through a surrogate modelling approach to reduce the time required while considering the entire possibilities of façade module adjustments. Then, simulation results were stored as.csv files to post-process them through a fuzzy logic method that allows addressing the existing uncertainty between what the users desire and how the modules should be personalized to achieve the highest possible visual satisfaction score. Ultimately, the following outcomes were discovered:

- By implementing the personalized control strategy, findings confirmed absolute visual satisfaction of two users from 83% to 100% during working hours, although the prioritization criteria could impact the façade module adjustments significantly where removing it could lead to higher fully-open modules to provide higher daylight and view outdoors.
- Among the three visual metrics (E_V, E_T, and VR) investigated in this study, the users' preferred E_V tolerance thresholds were met most of the time comparing with the other two metrics. This is mainly because the given priority to glare risk condition could adjust the individual modules in optimal positions to reduce the discomfort, while sufficient view to outdoors could also be provided for the users simultaneously. In addition, E_T values resulted from the optimal façade configuration generally showed relatively higher unsatisfactory values (i.e., lower than user E_T preference), although the 1st user with a relatively high task illuminance desire could be satisfied by 83% of the time. These findings indicate that providing indoor daylight level above 850lx could be a challenging task with the current façade modules' design despite the given higher priority over VR.
- There is a direct relation between users' preferences and their satisfaction rate. The 2nd user experienced higher satisfaction rate with respect to both E_T and VR due to lower desired range compared to the 1st user. While in case of E_V, the personalized control could deliver an absolute satisfaction for the 1st user with higher tolerance threshold.
- In case of user's view direction, whether east or west facing could not impact their visual environment significantly as opposed to their randomized visual comfort preferences. There is one exception which was impacted by the glare risk condition as the 1st priority where the personalized control dictated a closure tendency on the left portion of the facade for the user who is facing West for a limited time of the weeks (up to 6%).
- Following the previous research study limitation [43], keeping the personalized updated by the stochastic comfort preferences for each time interval could enhance the overall personalized control performance.

Furthermore, the comparative analysis between the proposed personalization control and typical automated Venetian blind controls revealed that the personalization method could effectively improve occupants' visual comfort through a consistent performance based on an overall comfort score during working hours especially in summertime. In other words, the façade modules could be positioned at the states by which sufficient E_T and VR values of both users would be provided while maintaining E_V values lower than maximum uses' tolerance. In contrary, the automated controls performance was subjected to a great comfort score inconsistency from 10 to 28 points where no single hour with highest comfort score could be derived. Even though the personalized and S2 were both
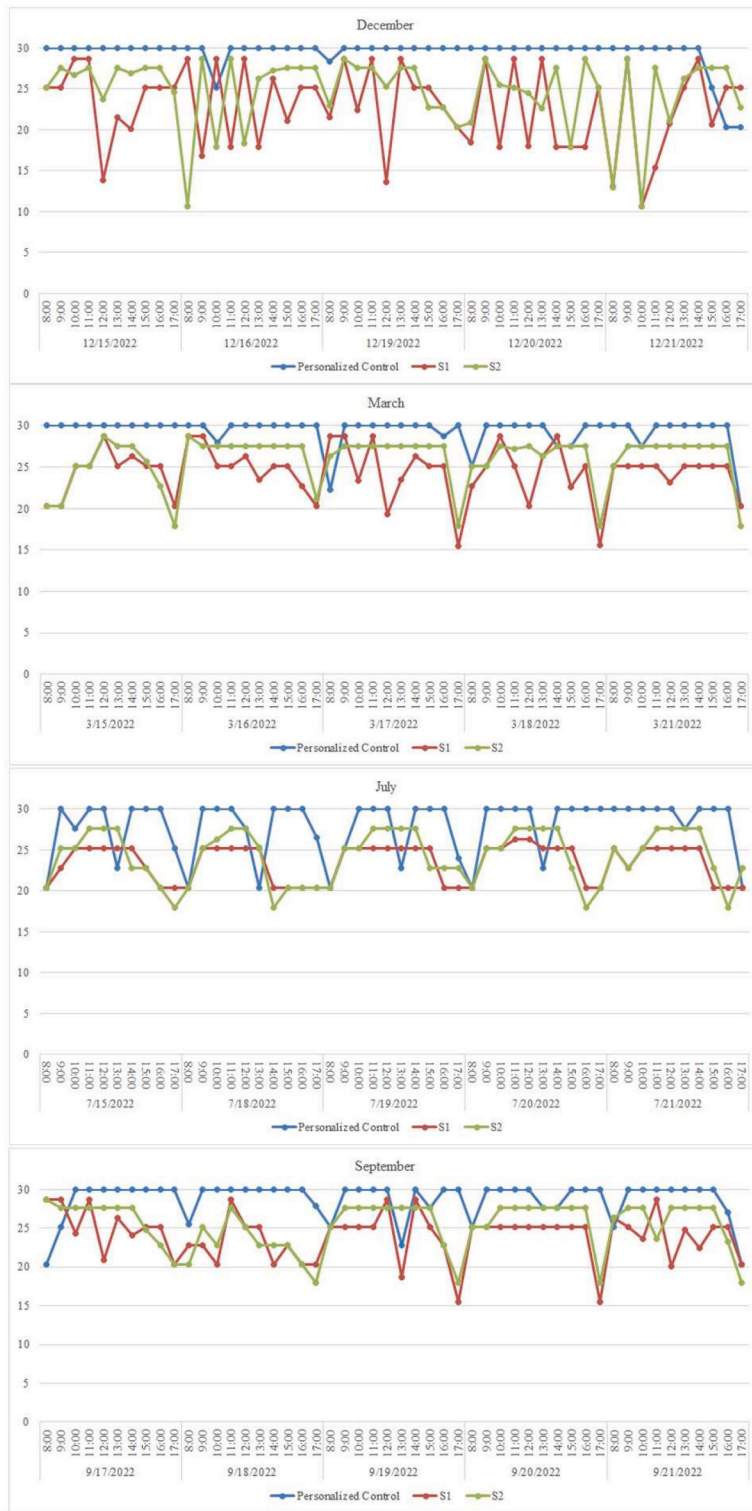
Fig. 15. Performance comparative analysis.

Table 8
Wilcoxon test and p-values.

	Personalized Control and S1	Personalized Control and S2
December	0.00	0.00
March	0.00	0.00
September	0.00	0.00
July	0.00	0.00

taking indoor environment conditions as the main control drivers (closed-loop controls), but the performance degradation of S2 was mainly due to automation based on a single objective (i.e., task illuminance) while ignoring other users' comfort desires (glare and view to outdoors). This means a multi-objective personalized control mechanism was found to be a necessity to address the multi-dimensional users' demands in a shared space.

4.1. Limitations

However, the research contributions and results should be used with caution and deal with certain limitations because of the developed simulation-based workflow:

- Thermal comfort was excluded from the research because of two main reasons: (1) building simulation tools are still not capable of assessing thermal comfort in a localized format, and (2) as derived from literature review, the main control driver of shading systems in air-conditioned spaces is visual comfort rather than thermal comfort.
- The number of modules and shading positions per modules were limited to 12 modules and 4 states to represent as a case study, while the original design is flexible to be adjusted in many different shapes or extended on larger number of windows. However, increasing the number of shading possibilities could increase the simulation time significantly, but in practice could be higher through surrogated daylight modelling approach to satisfy the occupants' visual comfort demands in finer resolutions.
- Occupant preferences were selected as ranges randomly and varied individually to indicate two different personalities which could be derived from surveys or questionaries. Although this research was mainly focused on the methodological part of the control rather than qualification analysis such as [61] or considering the impact of mood and psychological aspects of occupants' behavior.
- Occupants' distance to the façade could add extra complexity in a shared space especially with respect to their task illuminance which was ignored in this research. Such integrations could also validate the simulation results against existing data collections.
- In open-plan offices, occupants are not expected to be working with exact similar behavioral profiles (e.g., presence/absence) as opposed to the current research assumption which a deterministic and similar occupancy profile was applied for both occupants for the simulation. Such additional variation could significantly impact the personalized control and façade performance on indoor comfort levels.
- To test the personalized control capabilities on mitigating potential visual discomfort of occupants, simulations were tested on an hourly time interval while a finer time resolution (e.g., 10-min intervals) depending on the real-time data collection from sensors could impact the observations differently.

4.2. Recommendations

There are multiple considerations that are sufficiently valuable for future investigations. Firstly, utilizing previous real-time data collections (e.g., surveys) as a basis to derive visual comfort criterion for individuals in a shared space and coupling them with the developed control methodology in this research can unquestionably evaluate the personalization impacts whether on indoor comfort or building energy performance. Secondly, the proposed adaptive façade is a non-conventional typology; however, the personalized control workflow could be implemented on decentralized Venetian blinds or roller shades which are typical shading devices in shared office spaces. Thirdly, targeting occupants' preferences in a shared space requires a well-organized set of virtual sensors as control inputs for adjusting the façade using back-end control algorithms and their integration into internet-of-things (IoT) devices for future operational frameworks. Besides, in relation to IoT, designing user-interfaces such as wearable devices and dashboards could render personal real-time information for building controls.

5. Conclusion

Shared office spaces are typically designed to increase communication while co-existing environmental distractions including noise, temperature, (day)light, and others, suggest ambient features of the local environment influence occupant behavior, satisfaction, and ultimately, well-being and productivity. In addition, diverse comfort perceptions among individuals add extra challenges to building control management systems to drive expected façade adjustments. This means achieving a general visual comfort measure might not satisfy individuals' desires. Thereby, this study developed a personalizing framework for an indicative grid-based modular adaptive façade to adjust its elements individually while considering two main aspects on an hourly basis in a shared space: 1) indoor environmental changes including glare, daylight, and view to outdoors with respect to outdoor climatic conditions and users' positions and view directions, and 2) stochastic users' visual comfort preferences on an hourly basis. From technical perspective, this research coupled surrogate daylight modelling for visual comfort assessment of two occupants with fuzzy logic by mathematical means to account for imprecise information (e.g., occupants' comfort preferences) and genetic optimization to deliver the optimum facade modules' position at each simulation time-step. Findings confirmed a significant visual comfort improvement for both users compared

with two typical automated Venetian blind controls during four representative weeks and revealed a multi-objective control mechanism was required as a response to multi-dimensional and conflicting users' desires in a shared space. The personalized control satisfied both users with distinguished preferences intimately above 92% of the time which suggested a valuable approach for future studies. The results increase the awareness of façade designers and engineers, building facility managers, and project stakeholders with helpful information to successfully extend the current study application towards personalized control systems.

Author contributions

Amir Tabadkani: Supervision, Conceptualization, Methodology, Software, and Writing – Review and Editing, Arman Nikkhah Dehnavi: Methodology, Formal Analysis and Software, Fatemeh Mostafavi: Investigation, Writing – Original Draft, Visualization, Hoorie Ghorbani Naeini: Visualization, Writing – Review and Editing.

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.

Supplementary Material

The following supporting data [62] provides hourly simulation datasets for each module configuration and python codes for fuzzy logic and genetic optimization used in this study. The material is freely available for future studies and replications.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jobe.2023.106118.

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