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Evaluation of blinds control techniques for daylight and visual comfort in complex real-world conditions

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Abstract

The presence of sensor networks to monitor environmental conditions and the automation of blinds and lighting systems controls is now commonplace in buildings, especially public ones with a high number of occupants. However, implementing control algorithms that are sufficiently reactive to variable sky conditions and that actually meet occupants' needs is still a challenge. In the present study, we investigate and compare advanced and simple control algorithms developed for a variable occupancy, open space, small sized conference venue. Operation and performance resulting from an optimized approach are assumed to be the benchmark strategy, and two other control algorithms of varying complexity are compared with it. Results show that the optimized control strategy performs best overall, but only marginally compared to the other two strategies. It performed especially well in meeting glare protection requirements, as a glare-related parameter was embedded into its objective function, but it also led to erratic movements of the blind slats' tilt and it required significantly higher computation times than rule-based control strategies. These two factors make it impossible to implement such strategy as it is in the real building, and indicate that a practical control implementation can be more effective than an optimal one.

Highlights

- Blind control strategies of different complexities are compared on a real case study building
- Overall performance of optimization algorithms outperforms simpler strategies, but only marginally
- Optimization algorithms still require too long computational times for practical applications
- Full modelling of the building geometry is challenging, surrogate models might provide higher computational efficiency

Introduction

Building automation is considered one of the key strategies to reduce energy consumption and help the energy transition, while guaranteeing indoor environmental comfort for building occupants (European Commission, 2018). Model based control systems, especially if calibrated against measurements, are a promising strategy to promote the optimal use of daylight within buildings un-

der transient conditions and variable occupants' requirements (Jain and Garg, 2018). However, careful attention must be given to the suitability of control parameters, which need to represent the actual expected performance, and to the models chosen for such scopes, as they need to respond very quickly to transient inputs. While researchers argue that complex scenarios can be tackled only with the use of advanced control strategies, e.g. based on machine learning techniques (Casini, 2022), market research suggests that blind and lighting systems installers tend to adopt simple geometrical and rule-based strategies despite the progress made in system control engineering (Katsifaraki, 2019). Poor performance of sensing hardware, control algorithms, and in-situ calibration protocols has been associated with a reduced adoption of daylight-linked controls for lighting systems (Bellia et al., 2016). These challenges are exacerbated in case of complex building scenarios, such as variable occupancy (occupant behaviour modelling challenges), facades with complex fenestration systems (optical properties modelling challenges), or multi-systems integration (multi-physics modelling challenges).

The automation of Venetian blind system controls requires careful consideration of all these challenges. Traditional approaches rely on geometrical features, using the so-called cut-off angle to tilt the blind slats so that they completely block direct sunlight, or on the signals from irradiance or illuminance outdoor sensors mounted vertically on either roofs or facades (Xie et al., 2020). More recent studies opted for model-based strategies, where the blind control strategy runs an optimization algorithm that typically maximises daylight access while preventing glare. These two objectives are represented by the illuminance level at the workplane and by a daylight glare metric respectively. The more commonly used glare metric is Daylight Glare Probability (DGP) (Wienold and Christoffersen, 2006), which was found to correlate well with the expected glare sensation in a cross-validation study (Wienold et al., 2019) and which now figures in the EN17037:2018 standard document (European Committee for Standardization, 2018). Xiong and Tzempelikos (2016) used DGP, vertical illuminance and horizontal illuminance in the objective functions to optimize the control strategy of the lighting system and of a roller blind mounted on a sidelit test room. The optimization algorithm implemented in that study ran an exhaustive search

to identify the optimal solution for each time step.

If limitations in the hardware used within a building management system are considered, the control strategy must strike a careful balance between computational speed for on-the-fly simulations and storage size for precomputed results. Assuming the use of *Radiance* for the daylight simulations (Ward Larson et al., 1998), performing a complete (*rtrace*) simulation at every time step would require an excessive amount of time to obtain final results and actionable decisions, even more so if an exhaustive search is performed at every time step to find the optimal configuration. On the other hand, storing the precomputed matrices for a 3- or 5-phase simulation would need a significant amount of disk storage.

This paper consider a specific case study building to represent a highly complex real-world scenario that takes some of the modelling challenges in automated Venetian blind control to the extremes. Given that nine possible blind configurations are defined for each of the four facades, the analysis considers 6561 permutations and evaluates them against three performance indicators, at room level and at eight sitting positions. Contrary to previous studies that used test rooms or side-lit case studies, such complexity introduced additional requirements to the modelling setup and led to the exploratory use of a black-box optimisation algorithm.

Methods

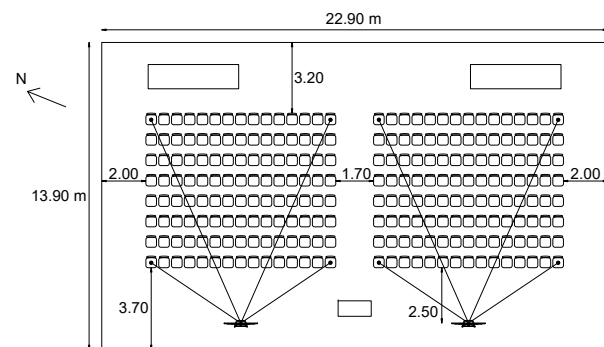
The building under analysis is a small conference venue with a capacity of 240 people and a rectangular floor-plan (Fig. 1), located in Delft, The Netherlands (52.0 N, 4.64 E; moderate sea climate). All four facades are completely glazed and supported by structural glass columns, which also bear the roof loads – more details about the building can be found in (omitted for blind review). Full-height Venetian blinds are installed on the exterior side of each facade and can be individually controlled; the slats are curved and are coated with a matte black paint. Daylight can also enter the space through four North-oriented, clear glazed rooflights situated on the flat roof. Most interior finishes are dark or black tinted. The interior space does not have any fixed furniture and can accommodate multiple furniture arrangements, depending on the type of event. The material definition used for modelling can be found in Table 1. Reflectance values were also used as variables to calibrate the model against sensor measurements from the real building (outdoor vertical illuminance and indoor ceiling illuminance), thus limiting simulation errors to a maximum of 20%.

Modelling methods

To calculate indoor horizontal and vertical illuminance values, daylight simulations were run with the *Radiance* 3-phase method – see (Subramaniam, 2017) for a manual describing input requirements – and blinds were modelled using BSDF materials (McNeil and Lee, 2013). This choice allows the storing of the view and daylight matrix, and their reuse in the final matrix multiplication with BS-

Table 1: Material optical properties, where ρ indicates visual reflectance and τ indicates visual transmittance.

Building element	Reflectance (ρ) or transmittance (τ)
Floor	$\rho = 0.3$
Ceiling	$\rho = 0.3$
Ground	$\rho = 0.25$
Blind slats	$\rho = 0.04$
Overhang / climate tower	$\rho = 0.01$
Neighbouring buildings	$\rho = 0.04-0.08$
Window-walls	$\tau = 0.68$
Doors	$\tau = 0.8$
Rooflights	$\tau = 0.8$



(a)



(b)

Figure 1: Floorplan (a) and exterior view (b) of the case study building.

DFs representing different blinds configurations, making the simulations more efficient. The Klems scheme is used as a basis for BSDF discretization for all illuminance-based simulations. To perform the glare evaluation, the enhanced simplified DGP method (eDGPs) was chosen, using vertical illuminances from the 3-phase method and direct sunlight luminance values from an *rtrace* point-in-time simulation with zero ambient bounces (Wienold, 2009). This approach was deemed accurate enough for the situation under analysis, given that the blind slats are painted with a matte black varnish and the reflectance of indoor surfaces is very low. The sky modelling part of the simulation makes use of the global horizontal irradiance that is measured on site by means of a commercial-grade pyranometer. Global measurements were then split

into their direct normal and diffuse horizontal components using the Skartveit-Olseth method (Skartveit and Olseth, 1987); results are shown in Fig. 2. Direct normal and diffuse horizontal irradiance are the required input for the Perez All-Weather model (Perez et al., 1993) that the 3-phase method uses to simulate the sky luminance distribution. The period 13-Mar-2022 to 20-Mar-2022 was chosen for the analysis as it represents mostly sunny conditions but with relatively low sun altitudes towards the end of the working day. A daily occupancy schedule was set from 8:00 until 18:00.

Control strategies

In the real building, the control of blinds, heating, cooling, ventilation and lighting systems needs to work in unison and needs to meet the requirements set for different scenarios, corresponding to different activities organised in the space. Facility managers can choose between different scenarios and override standard configurations but, in all cases, the occupants do not have direct control of the systems. This excludes the possibility to implement self-adapting algorithms, as proposed by Gunay et al. (2017), for example. For the current study, the analysis is limited to the investigation of the blind control strategies and to one space setting, whereby chairs and monitors are positioned as if a seminar was taking place (see Fig. 1).

Three different blind control algorithms are considered and compared in this paper.

1. Optimized control strategy. The optimization employed for the development of an ideal control strategy is based on the Radial Basis Function Optimisation (RBF-Opt) algorithm (Costa and Nannicini, 2018). RBF-Opt is a Python library for derivative-free black-box optimization, where the shape of the objective function is initially unknown. The significant advantage of RBF-Opt in comparison to other optimization algorithms is its ability to gradually construct an iteratively defined surrogate model, which approximates the shape of the fitness landscape that characterizes the objective function. With this method, the algorithm achieves to converge in robust results with high speed, rather than requiring an exhaustive search to find them.

RBF-Opt follows a three-stage algorithmic scheme. First, it decides an initial sample of possible solutions and defines the corresponding points of the fitness landscape. The latter is then gradually built-up with repetitive iteration steps that the algorithm determines based on the Metric Stochastic Response Surface Method (MSRSM), which employs a fast and simple genetic global search method. Every cycle of a certain number of iteration steps ends with a local step that tries either to improve the surrogate model in unknown parts or to discover the best objective function value based on the current surrogate model. The last stage of the algorithmic scheme is the refinement step, which is performed periodically during the global search and aims at improving the currently best solution by executing a local search around it.

Here, the objective of the optimization algorithm is max-

imization of the horizontal illuminance at desk level (E_h) provided solely by daylight. DGP acts as a soft constraint that ensures imperceptible glare risks ($DGP < 0.38$) for each time step of the analysis period. The constraint is imposed on the algorithm as a penalty, which, multiplied by E_h , constitutes the objective function, as presented below:

- If $DGP < 0.38 \Rightarrow \text{penalty} = 1$

- If $DGP \geq 0.38 \Rightarrow \text{penalty} = 0.0001$

$\text{Objective Function} = \text{penalty} \times E_h$

The blinds states are set as variables, which are specified by the algorithm in order to achieve ideal indoor visual conditions, maintaining optimal balance between horizontal illuminance and DGP. Since all blinds on each facade move simultaneously, there are four variables, corresponding to the BSDF material used in the North, East, South and West facades. For each variable, the algorithm chooses one of the nine available BSDF materials, which represent either an unshaded window pane or a fully-shaded window pane with a slat angle ranging between 0° and 80° in steps of 10° .

2. Rule-based control strategy. This approach represents a common rule-based strategy used for Venetian blind systems and primarily aimed at blocking solar heat loads. The blinds are pulled down whenever the vertical irradiance on an outdoor facade exceeds a defined threshold, typically in the range $100\text{--}300 \text{ W/m}^2$ (Van Den Wymelenberg, 2012). Here, as the sensors mounted on the building facades record illuminance, a threshold of 16000 lx global vertical illuminance (E_v) was selected, comparable to a 150 W/m^2 threshold under a sky with luminous efficacy of 110 lm/W . The tilt angle of the slats is defined by the cut-off angle, which always prevents direct sunlight from entering the space. In a nutshell, the rule-based control is described by the following logic:

- If $E_v \geq 16000 \text{ lx} \Rightarrow \text{blinds down, cut-off angle}$

- If $E_v < 16000 \text{ lx} \Rightarrow \text{blinds up}$

3. Control strategy applied in the real building. The control strategy applied in the building during the data collection period was a basic solar tracking strategy. The Venetian blinds on a facade are lowered when a threshold of 100 W/m^2 beam radiation for that facade is exceeded during more than two minutes. The slat angle for all blinds on a facade is set to 2° more than the cut-off angle. Whenever the beam radiation strength falls below 70 W/m^2 , the slats slowly open up beyond the cut-off angle to 0° (fully open) to allow maximum views of the outdoors. The blinds remain lowered for a minimum duration of half an hour and may go up again whenever the beam radiation strength falls below 50 W/m^2 . Direct and diffuse radiation strengths were computed from four differently oriented illuminance sensors by making a least squares fit to a Perez sky model. The currently implemented control strategy is summarized as follows:

- If beam radiation $\geq 100 \text{ W/m}^2$ for more than 2 min $\Rightarrow \text{blinds down, cut-off angle} + 2^\circ$

- If beam radiation $< 70 \text{ W/m}^2 \Rightarrow \text{blinds down, horizontal angle, for a minimum of 30 min}$

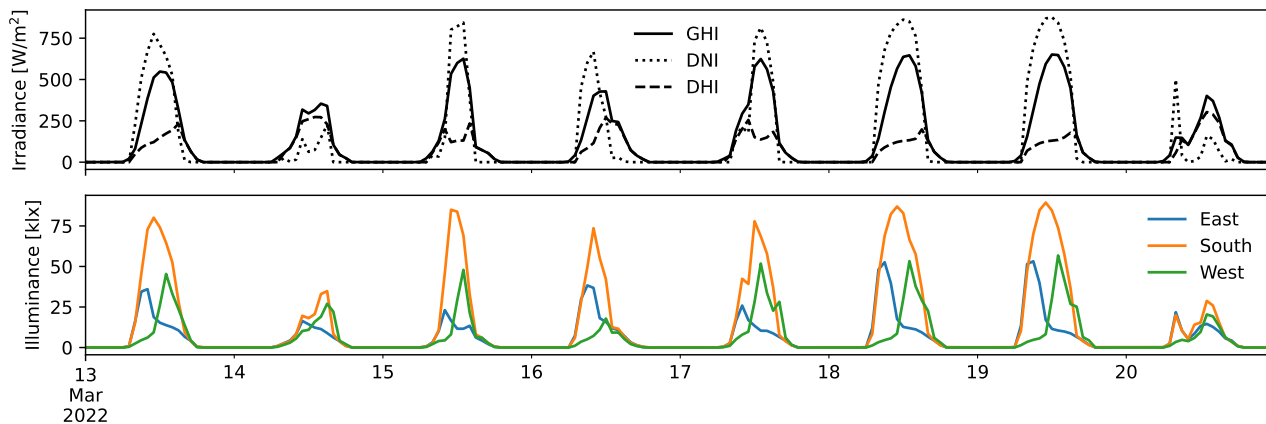


Figure 2: Global irradiance measured on the roof of the building, direct and diffuse components derived from it (top) and vertical illuminance measured on three sides of the building (bottom) during the test period.

- If beam radiation $< 50 \text{ W/m}^2 \Rightarrow$ blinds up

Key Performance Indicators

To compare the performance of the investigated control algorithms, the following indicators are calculated for each of the three investigated strategies: (a) daylight sufficiency, quantified by simulating the horizontal illuminance at desk level (E_h , $h = 0.80 \text{ m}$) due to daylight alone, and corresponding electric lighting consumption (in KWh) to reach the target level of 300 lx , considering a lighting power density of 7.45 W/m^2 ; (b) protection from discomfort glare, quantified by counting the number of positions, among the eight considered, that do not experience any discomfort glare ($eDGPs < 0.38$). This requirement is considered fully met only for hours when all eight positions do not experience discomfort glare; and (c) view to the outdoor, quantified by counting the number of facades, among the three visible from the considered sitting positions and directions (South, West and North), that provide a view to the outside, i.e. blinds pulled completely up or positioned with a slat angle of 0° (horizontal tilt). This requirement is considered met when two out of the three facade visible from an occupants' point of view provide a view out. All indicators are considered only within occupied hours. For the simulation of the $eDGPs$ indicator, the actual geometry of the blinds was modelled rather than using BSDFs.

To summarise these three performance indicators in a single value, allowing direct comparison between the effectiveness of each control strategy, an additional 'average satisfaction index' is calculated. This index represents the average between the previous three indicators, when they are all expressed as the numbers of hours that satisfy the set requirement. Depending on the type of space and investigation, one might assign different weights to such requirements and quantify the control performance as a weighted average.

Results

Fig. 4 shows the variation in the three performance indicators over the test period, together with the slat angle determined by each control strategy. Weekend days are shaded

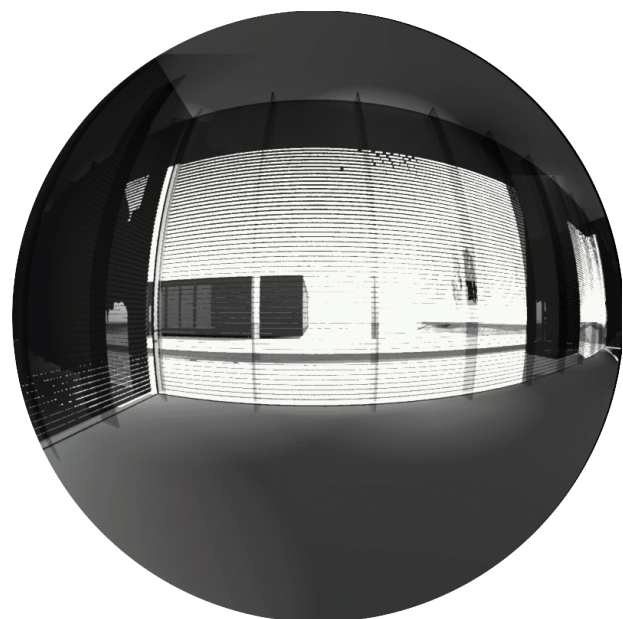


Figure 3: Example of a rendered view from the inside of the building, looking towards South.

in grey, to highlight the fact that the current control strategy behaves differently for occupied and non-occupied instances. In fact, the actual building follows two different control modes, one prioritising energy management when there are no occupants and the other prioritising indoor comfort when occupants are present. This explains the limited blind operations observed during the weekend, especially during overcast days when solar heat does not need to be blocked (see day 2022-03-20 in Fig. 4c).

It is noticeable how the slat tilt in the rule-based control is operated in a much smoother manner than the other two strategies. The optimized strategy in particular shows very abrupt changes between blind configurations for the different facades; while this behaviour might be necessary to guarantee the optimal performance, it might create discomfort and distraction to occupants.

The horizontal illuminance levels are almost always maintained within the range $300\text{--}5000 \text{ lx}$ when using the op-

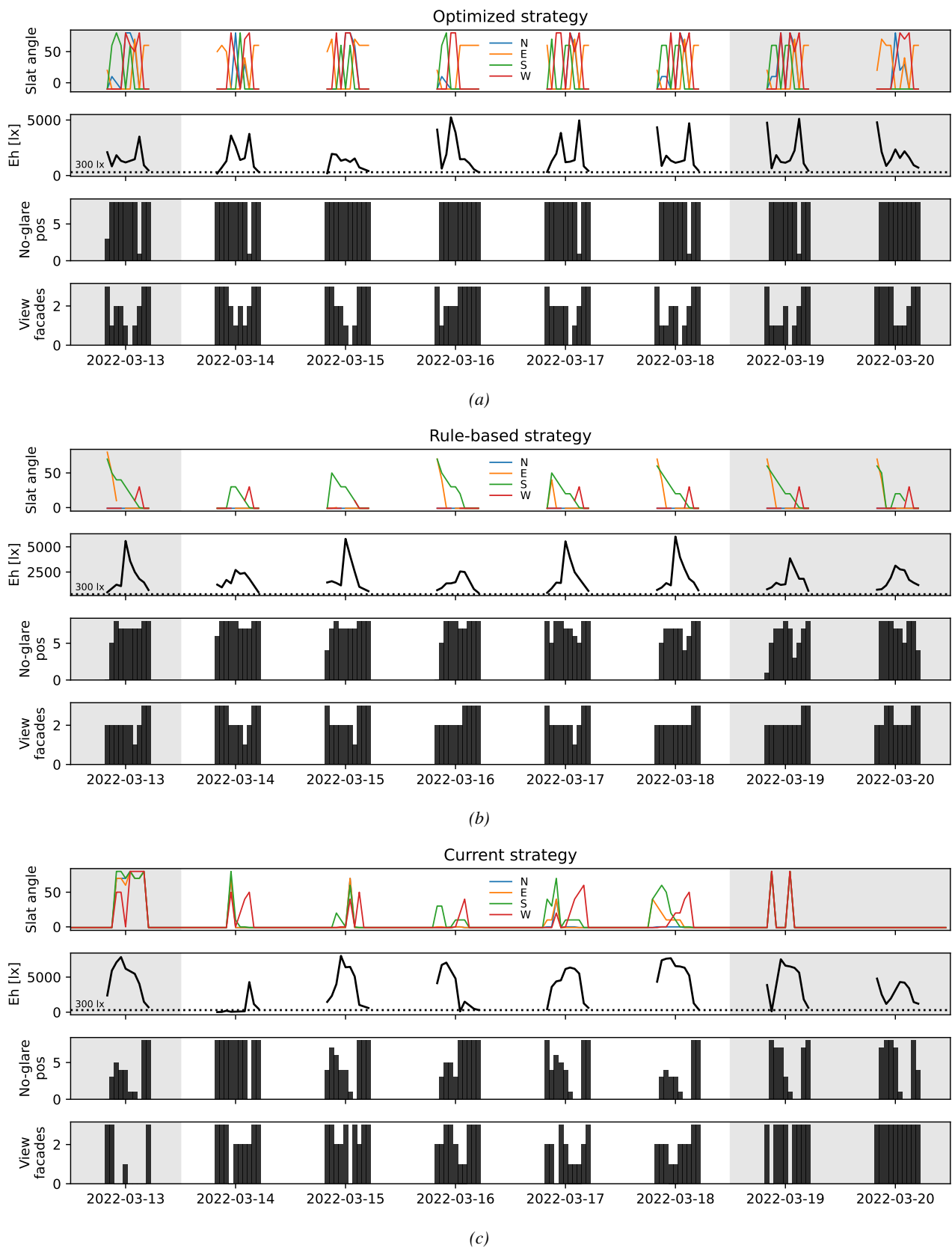


Figure 4: Results (slat angle, horizontal illuminance, glare index, and view index) for the three strategies: (a) optimized; (b) rule-based; and (c) currently implemented.

timized and the rule-based strategies, while they reach higher (up to 8000 lx) and lower (down to 25 lx) levels with the current strategy. Electric lighting energy is therefore not used at all in case of the rule-based strategy, only for two hours in case of the optimized strategy, and for nine hours in case of the current strategy.

Protection from glare at the eight sitting positions is almost completely guaranteed by the optimized strategy, which has a soft constraint $eDGPs < 0.38$ embedded in its algorithm, but less so by the other two strategies, in particular by the current one. The rule-based strategy is able to block glare for most positions by simply blocking direct sunlight, but not always for all eight positions. This might be an indication that discomfort glare affecting those sitting positions is not only caused by direct sunlight but also by specularly reflected sunlight, for example on other glass facades not protected by blinds. It was noticed that in some instances even the optimized algorithm could not find combinations that guaranteed a fully glare-free environment. The reason behind this is the presence of glass doors that cannot be shaded and through which direct sunlight can enter the building, especially for low sun angle instances. This was found to happen in the evening – through the West door, in the gaze direction of the occupants – and even in the morning, when the sun shines through the East doors and is reflected on the West inner glass facade, back to the occupants' eyes, causing disturbing glare.

View towards the outside is provided for most instances by the rule-based strategy, which always leave the North facade open as direct sunlight does not fall directly onto it in March. The view provision resulting from the optimized strategy is more erratic, as the blinds are constantly moved to meet the objectives of the optimization function, which does not include constraints on view-related parameters. For the current strategy, the view is blocked more during weekdays, when glare protection is prioritised, but it is left more open during weekends if the building requires solar heat loads to meet its energy management objectives.

In terms of computational times, results from the optimization algorithm took 5–6 minutes per each time step, whereas results for the rule-based strategy took 0.01 second per time step on an Apple M1 Pro processor. The time constraint implemented in the actual control system requires operations that can be completed within 3 seconds.

To draw a more direct comparison between the performance of the three control strategies, the three indicators are summarised as number of hours that satisfy each requirement. Such summary can be seen in Fig. 5. The daylight sufficiency requirement is met for most hours with the optimized and rule-based strategies, but for slightly less hours for the current strategy, mainly due to the blinds' behaviour on the day 2022-03-14. These illuminance levels lead to a total lighting energy consumption of 4.7, 0.0, and 21.3 kWh for the three control strategies respectively. The protection from glare requirement is best

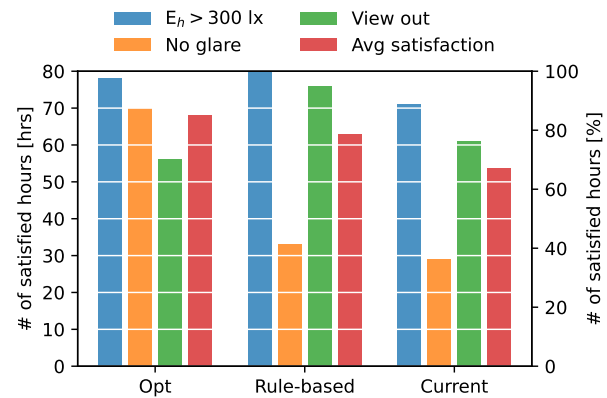


Figure 5: Summary of the key performance indicators for the three analysed strategies.

met by the optimized control strategy (88% of the time), as expected, compared to the other two strategies (40% of the time or less). The view out requirement is met for 70-90% of the time by all strategies, with the rule-based one providing the highest frequency of blinds configurations that guarantee a view to the outside from at least two facades. This is caused by the fact that the rule-based control never instructs the blinds on the North side to close, whereas the other two strategies do.

The last index shown in Fig. 5 aims at summarising in one value the level of satisfaction provided by the three control strategies. This index is calculated as the average number of hours from the previous three performance indicators, hence it does not represent – strictly speaking – a meaningful number of hours when all requirements are met, but an average performance of the control system in meeting such requirements, whether explicitly embedded in the control algorithm or not. The optimized algorithm scores the relative highest in such index, followed by the rule-based one and then the current one. The difference between the satisfaction index for the three strategies is however not very pronounced, with all three of them falling within the range 68–85%.

Discussion

Results show that the three control strategies, different in implementation and required effort, do not necessarily lead to an extreme variation in overall performance. The biggest performance difference can be found in the glare protection index, as the optimized strategy is explicitly designed to prevent discomfort glare, while the other two strategies are not able to account for glare caused by secondary sources (e.g. glass surfaces that reflect direct sunlight).

A number of assumptions and limitations had to be adopted in the present work, starting from the choice of the test period and its hourly resolution. In the actual control configuration, the time resolution is obviously much higher – in the order of seconds – as is the tilt angle precision. Here only tilt angles on the exact hour were considered and their value was rounded up to the closest multiple of ten. The real control strategy is therefore capable

of much smoother operations than shown here. ‘Smoothness’ was found to be an important parameter to keep into consideration during operation of the real building, one that is rarely taken into account when testing optimal control strategies in simulation environments.

As for the optimization algorithm, for the present analysis it was left running for 10 iterations but this does not guarantee that the global minimum is found in all cases. More iterations would provide a higher certainty that the global minimum is reached, and could even result in a smoother transition from one timestep to the next, but this would require even longer computational times. Furthermore, the used optimization is based on mixed-integer non-linear programming. Constructing surrogate models that correlate interior daylight levels and glare risk with defined blind configurations could allow the use of more efficient optimization algorithms based on linear programming, as suggested by Motamed et al. (2020). This approach would still require the *a priori* construction of a reliable and accurate model that represents the real environment, a challenging and time-consuming task for most buildings. In addition to this, any significant change to the outdoor or indoor environment could compromise the correlation between simulation and reality.

The geometrical model used in this work required itself a number of simplifications due to the high computational times. For example, window panes were not subdivided in smaller horizontal bands as it would be recommended to take into account the shadow created by the overhang surrounding all facades and other local obstructions. A subdivision of each pane in n bands would lead to $48 \times n$ the number of *daylight matrices* and *view matrices*, an amount that could easily cause memory overload. In the present work, the 48 *view* and 48 *daylight matrices* generated by the 3-phase method were loaded into memory, using over 700 MB of memory space.

Overall, the choice of ‘best control strategy’ requires a very careful consideration of the trade-offs between accuracy and overall efficiency at multiple complexity levels, related to shading device modelling, indoor and outdoor environment modelling, and potentially optimization models.

Conclusion

The present paper looks at the implementation of three different blind control strategies in a real case study building, whose daylight environment is modelled using the *Radiance* 3-phase method. The building offers a challenging environment to model, characterised by fully glazed facades, optically complex Venetian blinds, and variable occupancy and internal layout. The more complex control strategy among the investigated ones, based on an optimization algorithm that maximise daylight access while protecting occupants from disturbing glare, resulted in a slightly better overall performance than the other two strategies (7% more satisfied hours than the rule-based strategy and 21% more than the current strategies), but

was also characterised by frequent and sudden movements of blinds on all facades. The rule-based control strategy based on a commonplace irradiance threshold and cut-off angles, as well as the third control strategy representing the actual algorithm implemented in the building during the test period, scored lower than the optimized one, mostly because of the low protection from glare that they could provide to sitting occupants. However, the optimized strategy required about 30000 times longer to run than the rule-based one, making it unfeasible for implementation in real settings. Simplifying the geometrical model or using surrogate models might solve this issue but at cost of lower accuracy.

Supplementary data

The Radiance model of the case study building, the results and all the scripts used for the simulation and the data analysis can be found in the GitHub repository: <https://github.com/taoning/Daylight-Control-BS2023>

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