Comfort and efficiency-based improvements to the control of residential Venetian blinds

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Abstract. This study focuses on the control of movable Venetian blinds. Multiple improvements to an existing on/off open-loop control strategy in a case-study apartment have been simulated in TRNSYS 18, thanks to the detailed optical and thermal modelling allowed by the Bidirectional Scattering Distribution Function (BSDF) used as input to the Type56 CFS. The control strategy improvements include the combination of rule-based, closed-loop and discrete state control, in addition to four control strategy activation methods (three use a schedule, and one measures the external temperature). Simulated control inputs include internal temperature, external temperature and vertical irradiance. The results show reductions in overheating, achieved without completely blocking natural illumination or compromising heating demand. While on/off control in winter often leads to increased heating energy consumption, the space sees regular overheating when on/off control is inactive over winter. Conversely, discrete state control is able to more precisely control solar gains in winter to maintain an adequate temperature without utilising the heating system, all the while allowing some level of natural illumination. Ultimately, it is concluded that the choice of the control strategy depends on which objective (minimisation of heating energy consumption, maximisation of daylight harvesting, reduction of overheating risk, etc.) is prioritised.

1. Introduction
While renewable energy technologies continue to be indispensable for the decarbonisation of the energy system, the efficient use of energy is seen as a priority for the European Union; energy savings are the easiest way of reducing greenhouse gas emissions and saving consumers money [1]. Indeed, buildings represent an enormous opportunity for energy savings: they are responsible for some 40 % of all energy consumed across the EU. While non-residential buildings consume more energy per square metre, residential buildings make up the vast majority of the European building stock. In the residential sector, the largest end-use of energy is space heating at 68 %, although this figure is understandably lower for the Mediterranean countries [2]. In addition to passive measures to improve buildings’ energy efficiency, the EU foresees the installation of self-regulating devices to enable demand-based control building services [3]. With up to 40 % of workers having had to work from home since the outbreak of the coronavirus pandemic [4], the importance of comfort and efficiency in the residential sector is greater still.
1.1. Shading systems control

Multiple technologies are implemented in reviewed literature to manage visual and thermal comfort. Ahrendt et al. [5] compared some of the most commonly used control strategies for Venetian blinds. Simulations were carried out in various cities across the world to compare incident irradiance control, vertical illuminance-based control, cut-off angle control and blocking control along with static shading concluding that there is no universal best strategy. Indeed, optimal control of shading devices depend on numerous building-specific factors and ultimately the building occupants’ preferences. However, the two strategies involving sensors were better at minimising overall energy consumption and guaranteeing visual comfort simultaneously. The authors also emphasised that it is not always certain that active shading outperform static shading.

In the study by Uribe et al. [6], two high dynamic range (HDR) sensors with fisheye lenses were used to measure both horizontal illuminance and DGP, respectively. The analysed controller aimed to avoid glare while guaranteeing a minimum level of illuminance. It was found that the proposed control yields improved user satisfaction, with expected improvements in case of dimmable lighting (instead of on/off control).

Babu et al. [7] used traditional illuminance sensors, in addition to an HDR camera with a fisheye lens calibrated with a photometric sensor, to measure horizontal illuminance and DGP, respectively. Their analysis also aimed to keep horizontal illuminance between 500 lx and 3000 lx while maintaining DGP under 0.35. The study was successful in saving lighting energy and maintaining user comfort but concluded that façade orientation has a significant impact on the energy saving potential of such control.

Kunwar et al. [8] utilised several illuminance sensors placed around a room to measure horizontal illuminance (on a desk) and DGPs, in addition to an externally placed pyranometer to measure external irradiance, to control Venetian blinds and electrical lighting. The authors compared two control strategies: one open (external irradiance-based) and one closed loop (indoor illuminance-based). While both strategies were effective in achieving lighting and cooling energy savings, the closed loop strategy was more effective in preventing visual discomfort.

A recent study by Nicoletti et al. [9] aimed to improve a simulated residential building’s energy efficiency, while preserving visual comfort by automatically controlled Venetian blinds. The controls were rule-based and considered internal temperature, incident irradiation and the time of year. The control then chose the appropriate shading angle based on previous testing. Compared to a building with no slat control, the automated solution was able to save around 15 % in energy demand in both winter and summer.

In summary, the control of building façades has only become a focus of research in recent years, and the aim tends to be the management of visual comfort, often with the use of illuminance and DGP measurements; this is particularly prevalent in work environments where visual comfort standards may be in force. The additional consideration of thermal comfort in façade controls is less seen in literature. Studies are often focused on non-residential buildings: there are few examples of smart façades in homes.

The aim of this work is to see whether the addition of intermediate shading states and additional control inputs, as seen in the reviewed literature, could lead to efficiency and comfort improvements to an existing on/off open loop Venetian blinds control strategy in an Italian apartment.

2. Methodology

In order to evaluate possible improvements to a façade control in an existing model, 15 additional controls were simulated in TRNSYS 18, comprising of additional shading states and the use of internal temperature as a control input. The proposed controls’ effectiveness was evaluated in terms of heating energy consumption, overheating hours and shading hours.

2.1. Modelling

The reference four-person apartment was modelled and simulated within TRNSYS 18; in this work, only the south-facing living room was considered, with a volume of 64.0 m$^3$ and a floor area of 26.4 m$^2$.
The simulated weather data correspond to Florence, Italy. When the external temperature was greater than 16.0 °C, the internal temperature greater than 22.5 °C, and the external temperature less than the internal temperature, natural ventilation was exploited, otherwise mechanical ventilation was used. Assuming the external CO$_2$ concentration to be constantly 400 ppm, the infiltration rate to be constantly 0.16 h$^{-1}$, and the metabolic rate to be 1 met, the mechanical ventilation rates for the living room were precalculated, according to an occupancy schedule to attempt to keep the CO$_2$ concentration under 1750 ppm with a maximum volumetric flow rate of 35 m$^3$ h$^{-1}$. The heating system was modelled as ideal with a setpoint of 20.0 °C. The reference apartment was modelled without a cooling system, as is indeed typical of European apartments [10]. The thermal properties of the building envelope components are reported in Table 1, representative of a very well insulated apartment. In addition, the overall thermal conductance of the thermal bridges within the window (glazing/frame and frame/wall) was equal to 0.561 W K$^{-1}$. Note that the living room was coupled with the kitchen airnode, with a mass flow rate of 400 kg h$^{-1}$.

Table 1. Thermal transmittance and boundary conditions for the different building envelope elements.

| Construction type      | U-value [W m$^{-2}$ K$^{-1}$] | Boundary type            |
|------------------------|-------------------------------|--------------------------|
| Internal wall          | 1.638                         | Adjacent thermal zone    |
| External wall          | 0.208                         | Outside                  |
| Ceiling / Floor        | 0.415                         | Adiabatic                |
| Wall against stairwell | 0.783                         | Adiabatic                |
| Window frame           | 0.789                         | Outside                  |

The thermal and optical properties of the existing triple glazed window are reported in Table 2. The mixture between the glass panes was 10 % air, 90 % Ar. The window was modelled using the complex fenestration system in TRNSYS 18, whereby the optical model is based on a Bidirectional Scattering Distribution Function (BSDF) and the thermal model representing the glazing and shading elements is based on the ISO 15099, 2003.

Table 2. Thermal and optical properties of the fenestration system.

| Shading state          | U-value [W m$^{-2}$ K$^{-1}$] | g-value [-] | T$_{vis}$ [-] |
|------------------------|-------------------------------|-------------|---------------|
| Open                   | 0.736                         | 0.510       | 0.551         |
| Closed (blackout)      | 0.653                         | 0.030       | 0.004         |

The geometry of the glazing and the integrated Venetian blinds’ slats are reported in Table 3. The blinds were located between the external and central panes of glass.

Table 3. Geometry of the glazing system and of the integrated Venetian blinds.

| Glazed area [m$^2$] | Slat width [mm] | Slat spacing [mm] | Slat rise [mm] |
|---------------------|-----------------|-------------------|----------------|
| 1.538               | 10.0            | 1.0               |                |

The gains due to occupants [11], appliances and lighting [12] are reported below in Table 4. Occupant gains are combined with an occupancy schedule from Wilson et al. [13]. Appliance gains were multiplied by 0.6 during occupied hours after 08:00 and before 23:00 and by 0.1 otherwise, based on previous work [14]. Lighting gains were only considered during occupied hours after 08:00 and before 23:00 and when incident radiation on the façade was below 140 W m$^{-2}$.

Table 4. Internal gains.

| Source          | Scheduled gain | Radiant fraction | Convective fraction | Latent fraction |
|-----------------|----------------|------------------|---------------------|-----------------|
| Person          | 126 W per$^1$ | 0.18             | 0.42                | 0.40            |
| Appliances      | 8.0 W m$^{-2}$| 0.50             | 0.50                | -               |
| Lighting        | 2.7 W m$^{-2}$| 0.50             | 0.50                | -               |

2.2. Definition of the existing control strategy

There were three objectives of controlling the Venetian blinds:
1. The reduction of solar gains in the summer to avoid overheating. As previously said, the modelled apartment does not have a cooling system, therefore the effectiveness of solar gains control was evaluated by counting the number of timesteps when the internal temperature exceeds the conventional cooling setpoint of 26.0 °C.

2. The minimisation the heating energy consumption in winter by exploiting solar gains.

3. The maximisation of daylighting: it was desired to have the shading open as often and as much as possible to both avoid the use of artificial lighting and to maintain a pleasant, naturally illuminated space.

The existing control strategy for the Venetian blinds was on/off, open loop, and only active from 15 March until 15 November. On/off control means that the blinds can only assume two possible states (fully open or fully closed). A hysteresis controller was used which reduces frequent opening and closing to avoid disturbing inhabitants. When external vertical irradiance surpassed 140 W m⁻², the blinds were fully closed, but would not open again until external vertical irradiance fell below 90 W m⁻².

A 10-minute timestep was used. The following KPIs were calculated: (i) heating demand [kWh] (of the living room), (ii) the total time at each shading state [h]; (iii) the total time for which the living room temperature exceeds 26.0 °C [h].

Before any modifications, the existing control strategy discussed above leads to the internal temperature variation shown in Figure 1 in yellow and to the monthly heat balance shown in Figure 2 (Smr). It can be clearly seen that while the control is active (15 March – 15 November), it is often able to avoid overheating. However, when inactive (16 November – 14 March, the heating period according to Italian regulations for Florence), overheating occurs on multiple occasions due to the combined effect of high solar and internal gains. The heating, however, is never active – the temperature never falls below the setpoint of 20.0 °C. The total number of shading hours is 2055.2 h. The simplest change that could be made to the control strategy, in order to better understand how it could be improved, was to remove the ‘summer-only’ activation, and let the simulation run all year; the results of which can also be seen in Figures 1 and 2. The external air temperature and overheating threshold of 26.0 °C are also shown for reference.

Figure 1. Temperature variation for existing control – active in summer and active all year.

Figure 2. Monthly heat balances for existing control – active in summer (Smr) and active all year (AllYr).

Understandably, the total number of shading hours rises to 2808.7 h. While winter overheating is avoided by the control being active all year round, it leads to the internal temperature falling below its setpoint of 20.0 °C on several occasions, causing an annual heating demand of 0.48 kWh, although this is barely visible in Figure 2. This demonstrates something which severely limits the existing control strategy’s effectiveness; there are some situations in which it is simply unable to maintain a comfortable temperature: when the blinds are closed, it becomes too cold (activating the heating), and when open, it becomes too hot. Based on the behaviour of the existing controls, several improvements were proposed as follows.
2.3. Control strategy improvements and implementation

Three improvements to the existing control strategy are proposed: (i) the use of intermediate discrete shading states, (ii) the additional use of internal temperature as a control input, and (iii) two additional activation schedules and an external temperature-based activation rule.

A suitable alternative to on/off control is discrete state control, in which there exist multiple intermediate states for the blinds. Indeed, all of the reviewed studies in the literature implement control strategies where blinds can assume one of several discrete states. Many studies also integrate lighting control with façade control and conclude that lighting is far more precisely controlled when it can assume one of many states (dimming control) compared to on/off control. As in [5] and [9], the intermediate states chosen were the so-called cut-off angles, defined as the tilt angle beyond which no direct radiation is transmitted through the slats. The cut-off angle is calculated from the vertical shadow angle (VSA) and given by equations (1) and (2):

$$VSA = \arctan \left( \frac{\tan \alpha}{\cos \gamma - \gamma_w} \right),$$  \hspace{1cm} (1)

$$\beta_{cut-off} = \arcsin \left( \frac{d}{w} \cos VSA \right) - VSA,$$  \hspace{1cm} (2)

where $\alpha$ is the Sun altitude, $\gamma$ is the Sun azimuth angle, $\gamma_w$ is the window’s azimuth angle, $d$ is the slat spacing, and $w$ is the slat width.

In order to avoid the blinds moving too often and disturbing occupants, it was sufficient to have five discrete angles of the slats, plus one state in which the blinds are fully raised. As the analytical cut-off angle is just below 60° when the Sun is at its lowest in the sky, 60° was chosen as the maximum tilt angle. The remaining four angles chosen were 45°, 30°, 15° and 0°. The VSA angles for which the slats assume these tilt angles are reported in Table 5; these values are based on the analytical cut-off angle, and therefore specific to the geometry of the particular slats used in the apartment’s Venetian blinds. It suffices to define the discretised cut-off angle up to its maximum of 90°, and when VSA < 0° the Sun is behind the window, so no direct rays will enter the apartment and the blinds can be fully open. Within the software WINDOW 7.6, these five additional shading were defined. These shading layers were used to create five additional glazing systems. A BSDF file was generated, which combined all shading states. This was imported into a complex fenestration model in the Window Type Manager in TRNBuild.

| VSA [°] | Cut-off angle [°] | ID | U-value [W m⁻² K⁻¹] | g-value [-] | $T_{\text{vis}}$ [-] |
|--------|-----------------|----|---------------------|-------------|-----------------|
| [39, 90] | 0 | 1 | 1.009 | 0.463 | 0.480 |
| [30, 39] | 15 | 2 | 0.986 | 0.397 | 0.398 |
| [20, 30] | 30 | 3 | 0.927 | 0.299 | 0.277 |
| [8, 20] | 45 | 4 | 0.852 | 0.195 | 0.157 |
| [0, 8] | 60 | 5 | 0.777 | 0.120 | 0.079 |

Other than introducing discrete state control, variants in which the control is active all year, over the summer (15 March – 15 November) and over a ‘long’ summer (15 February – 15 December) are also proposed. In addition, a variant in which the control is activated when the external temperature exceeded 10.0 °C was also proposed.

As the existing control strategy was open loop, it seemed appropriate to also test a closed loop version. For on/off control, the internal temperature of the living room was used instead of incident irradiance in the hysteresis controller, with 24.0 °C and 22.0 °C as the upper and lower dead bands. In the case of discrete state control, internal temperature was used in conjunction with external irradiation as inputs, as explained in detail in Figures 3 and 4. All control strategies are summarised in Table 6.
3. Results

The results for each control strategy listed in Table 6 are graphically presented as follows in Figures 5 and 6. Note that Figure 6 only applies to the discrete state control strategies. No graph is presented for heating energy consumption, as apart from strategies 5 and 11, the heating energy consumption was zero; strategies 5 and 11 only used negligible amounts of heating energy.

The first thing that can be noted from Figure 5 is that the four different shading activation types all lead to similar overheating results, regardless of the control strategy – it is clear that summer-only control always leads to regular overheating, whereas control strategies active all year tend to minimise overheating. This is of course to be expected, as whenever the shading is inactive, the data for internal temperature and heating power are identical for all control strategies.

As already mentioned, there are only two control strategies leading to almost negligible heating energy use. This shows that this particular south-facing living room of this Florentine apartment requires no heating at all if solar gains are correctly exploited.

Again, in Figure 5, it is clear that the activation type similarly affects the shading time results of all control strategies, in that strategies active all year tend to result in more shading time, whereas controls only active in the summer tend to result in less shading time. The shading time tends to increase as the activation period is extended, suggesting the original activation schedule is unable to manage solar gains for this type of apartment and climate. It is important to remember that the total shading time is by no means an exact indicator of visual comfort nor of how much energy would be consumed by artificial lighting; the total shading time is a qualitative indicator for the amount of daylight not exploited. Indeed, in on/off control, the shading was fully closed, while in discrete control the slats could assume angles up to 60°. Clearly, the luminous flux through the Venetian blinds when set to any angle between 0° and 60° will be greater than when the blinds are fully closed, meaning that, qualitatively speaking, discrete
control will tend to lead to a more naturally illuminated space and reduce artificial lighting energy consumption.

Figure 6 shows that 0° is the most commonly set cut-off state for all discrete control strategies, corresponding to when the Sun is high in the sky. In addition, 45° is also regularly set when the internal temperature control strategies are active, because the strategy always sets the slat angle to 45° when the internal temperature surpasses 26.0 °C.

3.1. Further improvements
It is clear that the original control strategy (1) has been improved upon in terms of both total overheating hours and total shading hours. However multiple improvements could still be made to the model as well as to the controls to better evaluate their performance and to further optimise them. Firstly, it would be highly beneficial to integrate automatic lighting control into the model to keep areas lit to a given minimum level, such as 300 lx during the day ([5]). By doing this, the control strategies’ effect on electrical energy use could be quantified so that the advantage of avoiding overheating could be better compared with the disadvantage of reducing natural illumination. Alternatively, daylighting simulations could be carried out in parallel, and a suitable daylighting indicator chosen in order to better evaluate the controls’ effect on natural illumination. It would also be beneficial to investigate other factors affecting the apartment’s vulnerability to overheating, in particular internal gains and occupancy schedules.

It would also be beneficial to carry out more thorough tests in which all parameters are varied, such as the on/off controls’ dead bands, the irradiation value which determines whether the sky is clear or overcast, or the temperature below which the blinds are always completely opened in discrete control with internal temperature as an input. This would help determine whether it is the nature of the control strategies to yield results such as those seen above, or whether the choice of such parameters plays a considerable role.

Finally, it would also be useful to consider the control strategies’ effect on all thermal zones of the apartment. In this work, only the effects on the living room were considered, but by using the internal temperature of each respective thermal zone as the ‘internal temperature’ input to the shading function, each window could receive an individual shading function resulting in truly closed loop control. The heating energy use of the entire apartment could then be considered.

4. Conclusion
Clearly, the activation type greatly influences the effectiveness of the control strategy. Practically speaking, control strategies active all year are more effective as they can react to unusual environmental conditions, whatever the time of year. That said, control strategies activated based on external temperature performed similarly, and with some tuning (the threshold here was 10.0 °C) may yield the same results, however, this adds cost and complexity from a practical standpoint, and given these results, offers little improvement. Of the control strategies active all year, discrete control tends to lead to around double the overheating time with respect to the on/off controls; however, in absolute terms this amount is low, and some overheating in summer was found to be inevitable. The advantage of discrete control is that it allows some level of natural illumination while still reducing solar gains. Excluding on/off internal temperature control (strategies 2, 4, 6 and 8), all strategies yield similar total shading times, however, it is important to note that for every hour the shading is active in discrete control, the space will still receive some natural illumination whereas in on/off control artificial lighting most probably must be used. Discrete control can be thought of as less aggressive in its avoiding overheating, at the expense of increased natural illumination, thereby reducing electrical energy use and leading to a more pleasantly lit environment. Between discrete control strategies with external irradiation alone and external irradiation paired with internal temperature, there is little difference; the control strategies with internal temperature as an input tend to lead to fewer hours over 26.0 °C, at the cost of more shading time. Again, these small differences may just be a result of the exact parameters used in the control strategies and could be reduced by changing these parameters. One might conclude that the added cost
and complexity of internal temperature sensors outweighs their limited benefits. The results do show however, that for the considered case-study, in all cases closed loop control (with internal temperature as an input) is more effective than open loop control, given that overheating is always reduced when comparing control strategies with external irradiation and internal temperature as inputs. Therefore ultimately, deciding which strategy is most effective requires deciding which objectives are most important, as achieving one objective is often at the expense of another.

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