Automating Solar Shading Control in Residential Buildings Located in a Temperate Climate: A Household-Specific Decision

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Abstract

The implementation of movable solar shading is strongly encouraged in order to reduce the overheating of residential buildings. However, their efficacy is, amongst other factors, determined by the control system employed. Building occupants are often relatively passive in manually operating their shading, leading to suboptimal use, whereas automated control reacts consistently to changes in outdoor and indoor conditions. This study evaluates the impact of automated shading control on annual heating and artificial lighting energy consumption, and thermal comfort compared to manual operation in residential buildings without cooling installations. Building performance simulations are conducted for three building designs in the temperate climate of Belgium using EnergyPlus. Multiple variations are investigated to analyse the sensitivity of the impact of automated control to boundary conditions such as the orientation, reflectance of the solar shading, household composition and manual operation strategy. The results demonstrate that the implementation of automated shading control has the potential to substantially reduce thermal discomfort while exerting a minimal impact on the energy consumption. However, the relative differences in overheating show considerable variation, primarily influenced by the building design and occupant behaviour. These findings emphasise the necessity of considering co-benefits (e.g. thermal comfort) and boundary conditions when evaluating shading control strategies.

1. Introduction

There is an increasing demand for cooling in residential buildings in temperate maritime climates. From a technical perspective, this is driven by the enforced improvements in thermal resistance of the building envelope, combined with a decrease in the thermal mass in many new dwellings. In addition, this is reinforced by the building occupants, who are tightening their (thermal) comfort requirements. Moreover, the occurrence and severity of heat waves associated with climate change are also contributing factors. Many design guidelines recommend prioritising passive measures, such as the installation of solar shading, to reduce indoor overheating risks (Ozarisoy, 2022). However, their impact is highly dependent on the type of solar shading installed and its characteristics, as well as on the effectiveness of the control system (Tzempelikos & Athienitis, 2007).

The implementation of movable solar shades can enhance the thermal and visual comfort of the residents, while simultaneously reducing the energy demand in the case of active cooling (Yao, 2014). Nevertheless, the use of improper control strategies may lead to an increase in the total building energy consumption (Grynning et al., 2014). In this regard, the effects of shading on the artificial lighting energy consumption are often overlooked (Van Thillo et al., 2022).

The control of the position of solar shades should ideally reflect the prevailing and anticipated indoor and outdoor environmental conditions. Conventional manually operated shadings require the intervention of the building occupants, who typically show a rather passive attitude towards adapting the solar shading. Frequently, the closure of the shades is only initiated following a prolonged period of discomfort sensations. Furthermore, control actions are often associated with other activities, such as enter-

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Pernigotto, G., Ballarini, I., Patuzzi, F., Prada, A., Corrado, V., & Gasparella, A. (Eds.). 2025. Building simulation applications BSA 2024. bu,press.
https://doi.org/10.13124/9788860462022

ing or leaving a specific room, particularly for opening actions (Correia da Silva et al., 2015; O'Brien et al., 2013). This results in a hysteresis phenomenon between raising and lowering actions (Sutter et al., 2006; O'Brien & Gunay 2015). Consequently, manual operation leads to suboptimal control of the shading in residential buildings, particularly given that the residents are often absent during the hours of high solar penetration.

The automation of control allows the solar shading to act upon changes in the indoor and outdoor conditions. The efficacy of this system depends on the control approach selected, with scenarios designed to minimise overheating risks and daylight penetration potentially increasing the energy demand of artificial lighting. The configuration of control triggers, sensor positions and threshold setpoints therefore plays a pivotal role in determining the system's performances (Tabadkani et al., 2021).

In temperate climates, there is an increase in the risk of overheating, while many houses are not (yet) equipped with cooling installations. In these houses, the investment costs for automating the installation are not outweighed by reductions in cooling energy savings. Therefore, it is essential to consider the non-economic benefits in order to make informed design decisions.

It is generally assumed that well-tuned automatic control is more energy-efficient than its manually operated counterpart. The standard EN ISO 52120-1 proposes the BAC factor method to facilitate the estimation of this impact on the building energy demand (European Committee for Standardization (CEN), 2022). The corresponding BAC factor defines the cooling energy savings due to automated control at 20% compared to manually operated shading. Nevertheless, the impact of automated control on the heating and cooling consumption can differ by as much as 11% depending on the sensors employed, with solar radiation-based controls proving superior (Yao, Wang, et al., 2016). Furthermore, the actual impact on the energy consumption is also influenced by features related to the building and shading devices design (Van Thillo et al., 2022).

Similarly, the impact of automated shading on thermal comfort appears to be influenced by the building and its context. The efficacy of different automated control systems in reducing the operative temperature is, for example, affected by building design features such as the window-to-wall ratio (WWR) and orientation. In addition, the effectiveness of upgrading the control in improving the indoor environment is greater in climates with high seasonal variations (Tabadkani et al., 2021).

The building occupants themselves also exert a major influence, as they are directly responsible for the manual operation of the system (Littlefair et al. 2010). The effectiveness of their interactions will determine the level of thermal comfort and energy consumption of the baseline scenario (Yao, Chow, et al., 2016). Additionally, households have distinct habits related to the presence and production of internal heat gains. These interfamilial differences can have a substantial impact on the thermal comfort of houses.

Residential buildings differ in this way from office buildings with the latter typically exhibiting more regular occupancy patterns, which coincide with times of high solar gains. The majority of the studies related to shading control have focused on office buildings, as solar shading is likely to provide the most direct benefits in this type of building. In contrast, automated shadings are far less common in residential houses; although they could also provide significant benefits, especially considering that occupants will often not be in their home at times when solar gains are high and hence control actions would be appropriate.

This paper aims to determine the impact of automated shading control on annual heating and lighting energy consumption and overheating risk compared to manual operation in residential buildings without cooling installation. It is assumed that these performances are influenced by boundary conditions. Variations in occupancy behaviour (i.e. presence and manual operation) are therefore combined with diversity in the building and shading characteristics.

2. Building Performance Simulations

The energy and thermal comfort performance of residential buildings with manually operated and automatically controlled shading is contrasted through the use of building energy performance simulations. The annual heating and lighting energy consumption and indoor operative temperatures of all variants are simulated in EnergyPlus (version 9.6) with a simulation time step of 2 minutes.

2.1 Case Studies

The impact of shading control is evaluated for three different building designs of which the characteristics correspond to a recent detached, semi-detached and terraced building (Cyx et al., 2011). Each building comprises a living room with an open kitchen, three bedrooms, a bathroom, two toilets, a storage area, a corridor and an attic. The detached building also has a garage. All rooms are modelled as separate thermal zones.

The houses are situated in Uccle (Belgium), within a temperate maritime climate zone. The climate data utilised for Uccle is adopted from the International Weather for Energy Calculations (IWEC). Moreover, the set of simulations for each house is repeated four times, with each iteration representing a different orientation and corresponding variation in the solar heat gains per thermal zone.

Table 1 – WWR per orientation

Facade	Detached	Semi-detached	Terraced
Front	18.70%	7.18%	17.9%
Right side	27.52%	7.44%	-
Rear	15.02%	29.62%	39.2%
Left side	9.76%	-	-

The external walls of the houses consist of windows for 17.71%, 13.00% and 28.56%, respectively for the detached, semi-detached and terraced building, distributed over the different facades (Table 1). The entire building envelope is well insulated with a thermal transmittance of 0.1 W/(m²K) for the opaque constructions and 0.6 W/(m²K) for the windows and doors. The windows are further characterised by a solar heat gain coefficient of 0.5. Moreover, a timber frame construction, characterised by a low thermal mass, was chosen, resulting in a high potential for overheating.

During the winter months, the houses are heated continuously at 20 °C in the living room, kitchen, bedrooms and bathroom, while the corridor and storage room are kept at 16 °C. In contrast, there is no active cooling during summer months, but the building is equipped with external textile screens with an openness factor of 5%. Two types of screens are investigated, with reflectance values of 0.6 and 0.1 respectively.

The presence of occupants and the produced internal heat gains are generated probabilistically based on the Belgian Time Use Surveys of 2013 (Verbruggen, 2021). The associated lighting requirements are met by controlling the lighting installation automatically (Van Thillo et al., 2023). The performance of the case study dwellings is evaluated for 18 different households, ranging from one to six persons. For each number of inhabitants, three household routines are evaluated. From the ten generated patterns, the families with the minimum, average and maximum occupancy were selected to capture the variability between families.

2.2 Shading Control

The effects of automated shading control are compared to those of manual operation. Therefore, two manual operation strategies are considered in the simulations: in the first scenario the occupants tend to adjust the screens passively, while in the second scenario they interact more frequently. Although many occupants interact with their shading for reasons other than preventing solar gains (e.g. to darken their bedrooms), only the actions related to overheating are included here.

2.2.1 Passive manual operation

The majority of the building occupants exhibit a passive attitude towards the opening and closing of their shading in order to prevent overheating. It is anticipated that the occupants will close their shading when they are experiencing discomfort in their living room/kitchen or offices. For this scenario, the threshold is set to 26 °C for closing the shading on the condition that an occupant is present in the room (European Committee for Standardization (CEN), 2019). Conversely, the shading will be reopened upon the first entry into the room after the indoor operative temperature has dropped below 24 °C.

2.2.2 Active manual operation

Some occupants are more concerned about their thermal comfort perception and are therefore more proactive in operating their screens to anticipate on future overheating risks. Consequently, they will close the solar shading in their living room/kitchen and bedrooms as soon as they notice that the indoor operative temperature in one of these rooms exceeds 24.5 °C. In addition, they maximise daylight entrance by only closing the screens in the orientations where the solar radiation on the façade exceeds 150 W/m². Similarly, the occupants reopen them when the indoor operative temperature has dropped below 22.5 °C or the sun intensity on the window is less than 50 W/m². However, the family members show a more passive attitude towards opening actions, only opening the shades when entering a room.

2.2.3 Automated shading control

In this scenario, the solar shading is switched when sensor readings exceed predefined thresholds. A combination of an indoor temperature sensor and an outdoor solar radiation sensor are here implemented to control the position of the screens. They will close when the solar radiation exceeds 79 W/m² and the indoor air temperature simultaneously reaches 21 °C during the cooling season. During the heating season, this temperature is set to 24.5 °C to maximise the heat gains. Once a trigger has fallen below the threshold for a period of 20 minutes, the solar shading will reopen. In this scenario, all windows are equipped with solar shades and are controlled separately.

2.3 Impact Assessment

This study examines the impact of solar shading on thermal comfort and energy consumption. The energy performance is divided into two categories: space heating demand and artificial lighting energy. The thermal comfort performance, and more specifically overheating, is evaluated based on the indoor operative temperatures and room occupancy. In residential buildings, the comfort requirements depend on the function of the room. The rooms with short and irregular occupancy patterns (i.e. the corridor, toilets, storage and attic) are not included in this analysis. The remaining rooms can be classified into three groups with different requirements: (i) the bathroom, (ii) the bedrooms and (iii) other rooms (i.e. the living room and kitchen and home offices). Furthermore, the perception of indoor temperatures as acceptable is found to be strongly dependent on the recent outdoor temperatures. Therefore, the maximum comfortable temperature for each room type is determined as a function of the outdoor conditions (Peeters et al., 2009). For each time step and each room, the operative indoor temperature (θ_i) is compared to the corresponding maximum temperature by 10% PPD (θ_{max}) to identify any overheating risk. However, this is only included in the key performance indicator if there are actually occupants present at that moment. The degree of discomfort per time step is expressed as a function of the time step (t), the number of occupants (N) and the extent to which the comfort temperature is exceeded. Finally, the annual thermal discomfort of the family is calculated as the sum of the discomfort experienced in the different rooms and over all time steps using equation (1).

$$\text{discomfort} = \Sigma\Sigma\ t * N * (\theta_i - \theta_{max}) \text{ for } \theta_i > \theta_{max} \quad (1)$$

3. Results and Discussion

3.1 Impact of Automated Shading Control

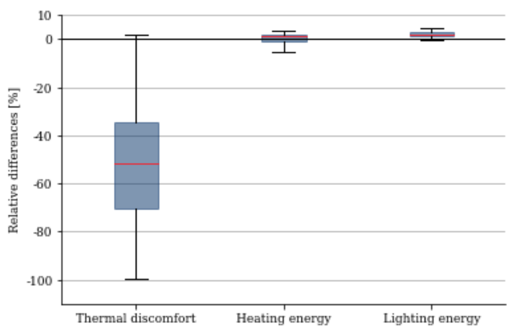

Fig. 1 – Impact of automated shading control

The simulation results indicate that the implementation of automated solar shading control can significantly reduce thermal discomfort for occupants, in comparison to manual operation. As presented in Fig. 1, the experienced overheating decreases by a median of 52.74% following the introduction of the automated control. In contrast, the median increase in heating energy and artificial lighting consumption is relatively small, with differences of 1.18% and 2.14%, respectively.

Fig. 1 indicates that there is a considerable variation in the improvements in thermal discomfort among the investigated combinations, with values ranging from a slight increase in the discomfort of 1.74% to a reduction of 99.36%, whereas the relative differences in the annual heating and artificial lighting energy are rather limited. However, it appears that the annual heating and lighting energy can both increase and decrease when automated shading control is implemented. In general, the relative differences in annual heating energy consumption range between an increase of 3.66% and a decrease of 5.89%. Although the annual heating energy increases on average, in 35% of the investigated variants the heating demand is slightly reduced as a result of automated shading control. In the case of artificial lighting energy, only in a very small minority of the cases (i.e. 4%) the energy demand decreases by automating the shading devices. These reductions are relatively small, with a maximum of 0.46% of the annual artificial lighting energy, while the increases reach up to 17.26%.

3.2 Influence of boundary conditions

A sensitivity analysis was carried out, varying the following parameters: building type, orientation of the building, reflectance of the solar shades, number of occupants, household routines, and manual shading control. A Wilcoxon signed-rank test with a 5% confidence interval was used to explore their influence on the differences in relative impact. The results indicate that each of the properties affects the relative differences to a greater or lesser extent.

As pointed out in Table 2, the impact of automated shading control on overheating is most significantly influenced by the differences in the building designs and the behaviour of the occupants. Of the latter, the number of inhabitants appears to have a more pronounced impact than their habits regarding shading control. In contrast, the reflectance of the screens seems to have negligible effects on the thermal comfort impact of shading control. Furthermore, the sensitivity of the impact of automated shading control on the annual heating and artificial lighting energy to the investigated boundary conditions is rather limited, except for the influence of the manual control behaviour on the heating energy consumption.

Table 2 – Median differences in relative impact of automated control for the investigated variations in the sensitivity analysis

Variation	Discomfort	Heating	Lighting
Building type	23.27%	1.20%	1.61%
Orientation	15.51%	0.93%	0.67%
Reflectance	1.94%	0.06%	0.07%
Number of occupants	28.59%	1.15%	1.21%
Household routines	3.44%	0.35%	0.25%
Manual control	19.21%	3.06%	0.06%

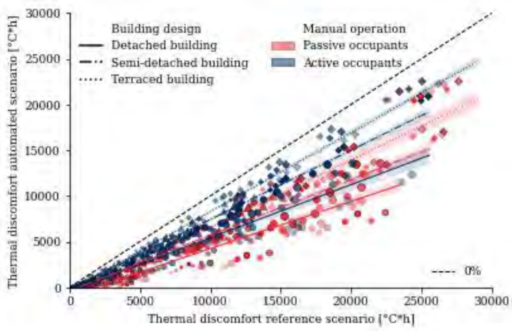

Fig. 2 – Linear regression of the impact of automated shading control on the thermal discomfort per building design

The investigated building types, namely detached, semi-detached, and terraced buildings, and their respective designs appear to have a major impact on the relative improvement in thermal discomfort when comparing automated control and manual operation of shading devices. A linear regression analysis, as presented in Fig. 2, indicates that higher reductions in the thermal discomfort are observed for the detached case study, followed by the semi-detached and terraced building. The results reflect the differences in window area between the case studies: automated control appears to be more effective in reducing the overheating risk in dwellings with a high glazed area.

3.3 Influence of Occupant Behaviour

The sensitivity analysis addresses various aspects of the occupant behaviour: the number of inhabitants, their routines regarding presence, and their habits for manually operating the screens.

3.3.1 Household composition

The composition of the family has a significant influence on the absolute discomfort experienced. The number of occupants is included in the calculation of the discomfort indicator, which means that higher occupation rates directly affect the absolute values. By normalising these results in relation to the total occupied hours, the differences are smoothed out. However, Fig. 3 shows that a lower number of inhabitants generally results in overheating during a smaller share of occupation or in a less extreme feeling of discomfort. The reduced risk of overheating is a consequence of the decreased internal heat gains that are associated with smaller households. Nevertheless, this trend is also subject to differences in family routines.

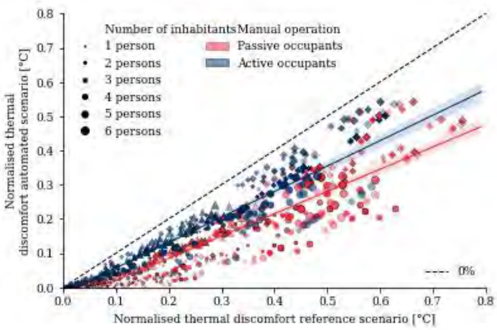

Fig. 3 – Impact of automated shading control normalised for the period of occupation

When considering the relative impact of automating the shading control, it is observed that the household size has a major impact, while their routines only have a limited influence. As presented in Fig. 4, the relative impact varies considerably according to the number of occupants due to differences in family composition and associated routines, as well as they are influenced by the other boundary conditions. Despite these variations, it appears that the relative improvements diminish with an increasing number of inhabitants, which may be attributed to changes in the ratio of external to internal heat gains, as well as differences in the degree of absolute discomfort.

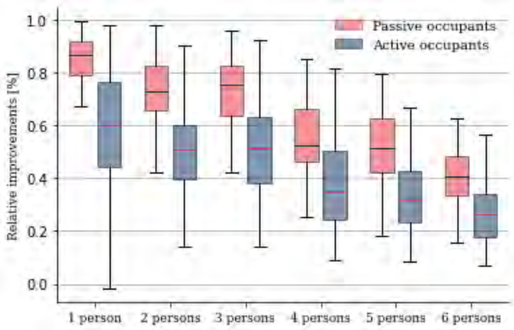

Fig. 4 – Relative improvements in thermal comfort per number of occupants

3.3.2 Manual operating behaviour

The interaction of occupants with the solar shading is identified as one of the most significant influences on the potential for automated control. Two distinct scenarios have been simulated: occupants with a more passive and more active attitude, thus representing two extremes in the range of manual control. The distribution of the results shows that this reference behaviour has a significant impact on the effectiveness of manual operation in reducing thermal discomfort, especially for increased occupancy. While the differences in heating demand are less pronounced, the automation of solar shading generally results in an increase in the annual heating energy consumption compared to a passive operation strategy. Conversely, there is a decrease in this consumption as the users interact more actively with their screens (Fig. 5).

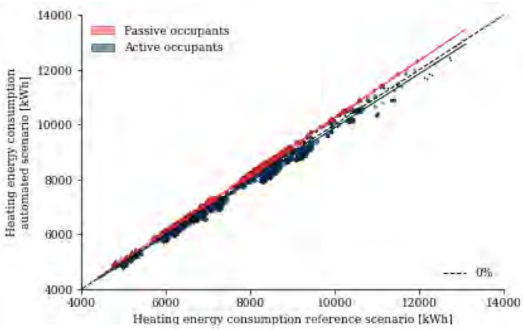

Fig. 5 – Influence of manual shading operation strategies on annual heating energy consumption

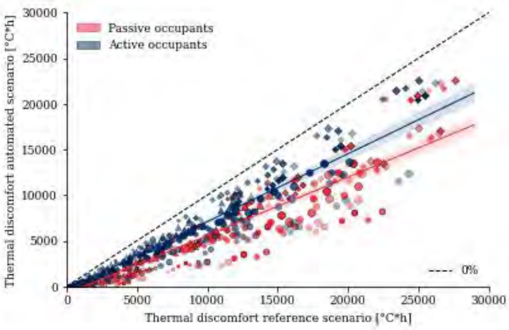

Fig. 6 – Influence of manual shading operation strategies on thermal discomfort

As illustrated in Fig. 6, the potential for reducing thermal discomfort by automating control is greater when occupants passively engage in manual shading operation than when they actively open and close their solar screens. More specifically, the median percentage reduction in discomfort when occupants interact with their shading in a passive manner (63.25%) is 1.59 times greater than when they are more actively involved in shading control operations (39.86%). The associated absolute differences are relatively limited for households with low absolute thermal discomfort, as the interactions are constrained by the presence of occupants, but gradually increase as the absolute values increase.

4. Conclusions

The implementation of automated shading control in a highly insulated residential building without cooling, located in a temperate maritime climate, can reduce the thermal discomfort by a median value of 52.74% compared to manual operation, with a relatively small impact on the annual heating and lighting energy consumption (i.e. a median increase of 1.18% and 2.14%, respectively). The relative differences in overheating exhibit significant variations, primarily driven by the number of inhabitants, the building type and the definition of the reference manual control behaviour, while they are to a lesser extent influenced by respectively, the orientation, household routines and shading reflectance. However, the absolute reduction in thermal discomfort is strongly related to the hours of occupation and the number of inhabitants.

The main impact of shading control is observed in the field of (thermal) comfort, particularly in dwellings without cooling, which is common in temperate maritime climates. Tools such as the BAC factor method of EN ISO 52120-1, however, focus on energy performance, whereas these impacts (i.e. on the annual heating and artificial lighting energy consumption) are limited for the investigated case studies. Moreover, they assume that automating the solar shading reduces the cooling demand by 20% compared to manually operated shades. This results in a reduction of the total energy consumption as the impacts on the heating energy demand and artificial lighting energy are not considered. However, the results of this study indicate that, on average, a small increase in energy consumption can be expected in houses without cooling, which leaves the economic investment unbalanced. Co-benefits as the reduction of thermal discomfort should be taken into account to support decisions, as well as boundary conditions. For the investigated cases, the susceptibility of the house to overheating and occupant behaviour affect the impact, while the presence rate and tolerance to thermal discomfort co-determine the benefits for a family. In future research, the set of influential parameters will be further extended to cover a broader range of buildings and contexts.

Nomenclature

Symbols

t	time (h)
N	number of occupants
θ	temperature (°C)

Subscripts/Superscripts

i	indoor operative
max	upper limit for 10% PPD

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