Evaluating annual solar heat gains from manually operated shading system

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Abstract

Occupant behavior towards manual solar shading systems affects the energy performance of buildings. Behavior depends on several aspects which interact in a nontrivial way. This paper presents a simple prediction model of behavior based on self-reported use of manual shading and a user survey. The specific model is applicable to the case study building, which is an office building in Gothenburg, Sweden, but the approach can be extended to other buildings. The model was tested against a hypothetical automated solar shading system for the same building. The results show that cooling loads increased by at least 25 % with the manual model in respect to the automatic system due to fewer blind movements. The results show that not accounting for occupant behaviour leads to a significative performance gap between predicted and actual building energy use.

Keywords: Occupant behaviour, Shading system, Annual solar heat gains, Prediction model.

1. Introduction

Occupant behavior towards shading systems has a major impact on heating and cooling loads (Hong & Hung-Wen, 2012). Studying behavior towards building systems and their interfaces is not trivial, as it depends on both environmental triggers and psychological processes (Gentile, 2022). While some behavioral models have been proposed for use of shading in respect to environmental triggers, for example LightSwitch-2002 (Reinhart, 2004), occupant actions related to other individual evaluations are not yet fully understood and are currently object of extensive research. As a result, simplified behavioral models are usually adopted by simulation software and a performance gap between simulated and performed energy performance has been often reported (Borgeson and Brager, 2008).

In relation to solar shades, the choice is usually between manual and automatic shading systems. Manual shading systems are often applied because of low installation and maintenance costs; however, it can lead to higher energy use. Automatic shading systems should perform better in respect to energy, but since shadings are generally chosen at late stages of building design (Yao, 2014), integrating shades automation in the building management system is complicated, if not impossible in real projects. In addition, real life projects suggest to to always provide a manual override to automatic shading (Gentile et al., 2022), which increases the uncertainties in real operation performance. Many building simulation programs for dynamic thermal and energy modelling consider the use of manual solar shades deterministically linked to changes in the luminous and/or thermal environment (Newsham, 1994), including incoming radiation on the facade, indoor temperature, glare (Fisekis et al., 2003), or daylight illuminance (Roche, et al, 2000). This approach requires typically the definition of occupancy schedules and set-points for temperature, facade radiation, or indoor lighting (Yao, 2014). Occupant actions on shades, however, are not necessarily completely aligned with the indoor environmental conditions. For example, once shading is lowered, occupants generally do not raise them back even if when the environmental conditions would suggest so (Scorpio et al, 2022). A deterministic approach to occupants' behavior overlooks the complexity of human behavior, which is, in the best of cases, of stochastic nature, see e.g., Reinhart (2004).

In general, occupants act on shading to 1) achieve visual comfort and allow access to view, and to 2) achieve thermal comfort (Katsifaraki, 2019), whereas visual comfort seems to be the main trigger for closing blinds (Van Den Wymelenberg, 2012). In addition, individual factors related to social norms or previous experiences are modulating such actions (Gentile, 2022).

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In this article, a model to predict the use of solar shading has been developed. The model uses both environmental information (glare probability, façade radiation) and individual factors to determine the use of shading. Since the individual factors are derived via a survey for a specific case building, the model is applicable as such only to that specific case. However, the approach for deriving the model can be extended to other case study buildings.

The model is then implemented in a simulation software and the energy performance of manual shades is compared to that of an ideal automatic one.

2. Methods

The study consisted of a collection of both technically measured and survey data on the use of shadings for a case study building. The data was used to develop the prediction model. The prediction model was used to test the performance of a daylight and thermal model with a manual shading system, whose operation was based on the prediction model, and an ideal automatic system (Fig. 1).

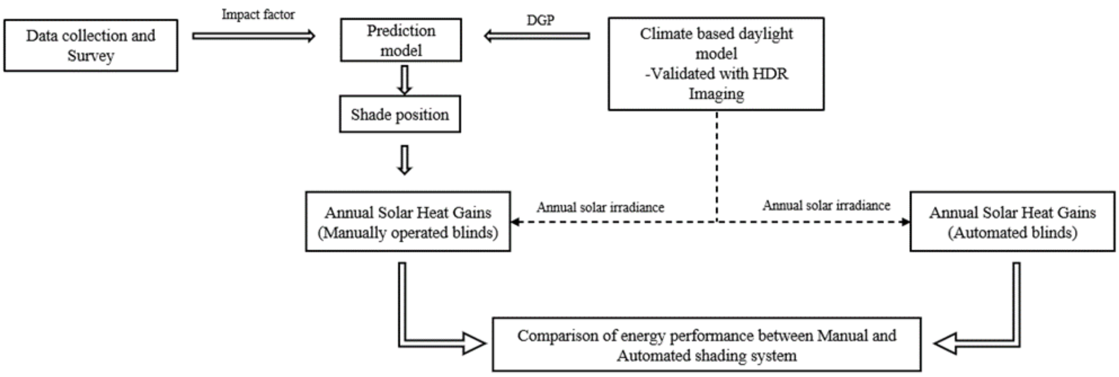

Fig. 1: Sequence of study

2.1 Case study building

The study was carried out on the fourth floor of an office building located located in Gothenburg, Sweden (Fig.2). The building has a window-to-wall ratio of 45 %. The office layout consisted of predominantly landscape offices, and few private offices around the courtyard. All offices are currently equipped with manually operated internal shades. The total heated floor area of the fourth level is 1 916 m^2.

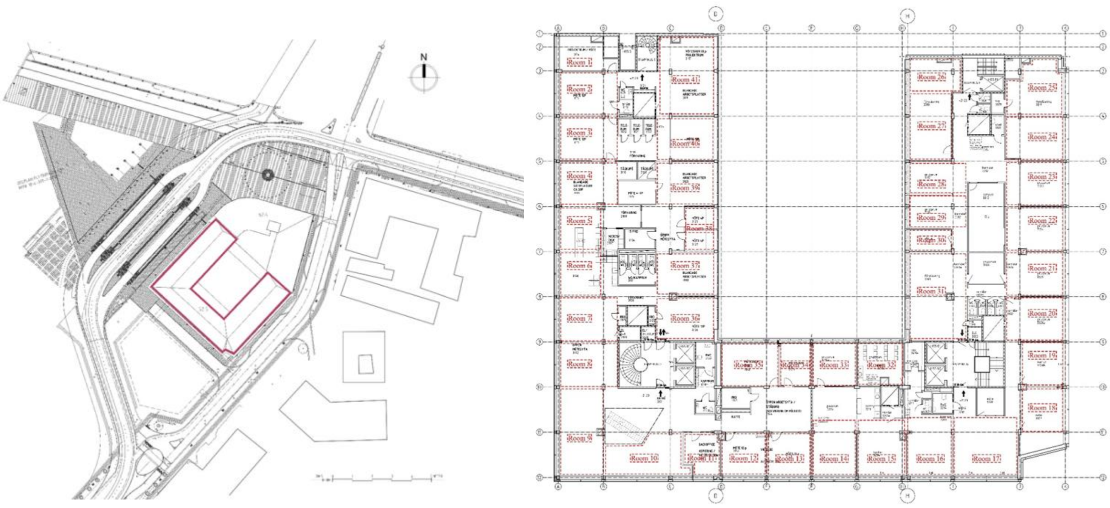

Fig. 2: Map and layout of the case study building

2.2 Existing daylight condition and visual comfort in the office building

A daylight and thermal model were drawn in Rhino. Image based-simulation and both horizontal and vertical illuminance values were validated against the measured data from both HDR images and illuminance meter. Daylight and energy analysis were performed via Honeybee and Ladybug plugins for Grassopper. Grid-based annual lighting simulations without roller blinds and electric lighting were run for the office building.

2.3 Survey and participants

The participants filled in the Lighting-Diary (Maleetipwan-Mattsson et al., 2013), which consist of a self-reported diary where they could log when they operated the solar shades with the approximate position (0% - 25% - 50% - 100% closed). The diary was filled during a week. It gave insights about individual actions on shades that could enrich the usage model based on only environmental predictors (visual and thermal comfort).

Participants were required to fill in a short written longitudinal survey concerning questions about general glare experience at their workplace and their perceived control over the shading system. The survey included open-ended questions and it was administered three times, at the beginning of the months of February, March, and April. On all occasions, there were clear sky conditions in Gothenburg.

2.4 Development and testing of the prediction model

The observations represented the base for the prediction model which is illustrated in Results. The validity of the prediction model was tested by visual documentation of the position of the solar shades in the real building during two specific days, 7th of March and 1st of April 2022, at 09:00, 13:30, and 16:00. The positions recorded in the real building were successfully compared with those predicted by the model.

2.6 Energy performance with the manual and automatic shading systems

2.6.1. Manual solar shading system

The solar shading position of the blinds in the private office rooms and landscape office were determined from the prediction model. Shades in common areas were assumed fully open throughout the year, as this was an outcome from the survey. Solar heat gains were calculated according to equation 1.

$$SHG = I.g.\frac{A_{glass}}{A_{room}} \quad [\mathrm{W/m^2}] \qquad \text{(eq. 1)}$$

Where I is the solar radiation against the glazing system with a solar factor g for the area of glazing A_{glass} in the room of area A_{room}. The g-value considers solar shades. The g-values for intermediate shading states were unknown. In such cases, the solar heat gains were calculated assuming that the shading position is installed on the exterior side of the glazing, reducing the glazed area. Then the solar radiation on the glazing surface was reduced proportionately instead of reducing the g-value of the glazing system with a partially closed shading system.

The Daylight Glare Probability (DGP) was calculated for the different shading states. According to the shading state, annual solar heat gains were later calculated using equation 1. Peak loads were calculated for the hour with the highest solar radiation; in such cases, it was assumed that shades were fully closed.

2.6.2. Automated solar shading system

The automated shading system had a set-point of 150 W/m^2 on the façade, which is a common threshold in northern Europe (Wienold et al, 2011). The automated shading could be either fully open or fully closed. The annual solar heat gains through the automated shading system were calculated based on this control algorithm using equation 1 and later compared with the manual shading system. Peak loads on each room were also calculated based on the same control algorithm.

3. Results

3.1 Daylight and glare analysis

The existing daylight conditions in the building suggest that there is a relative high glare risk in most of perimetral zones of the building. The office area is well daylit, with a DF_{mean} of 4.3 and a DF_{median} of 3.2.

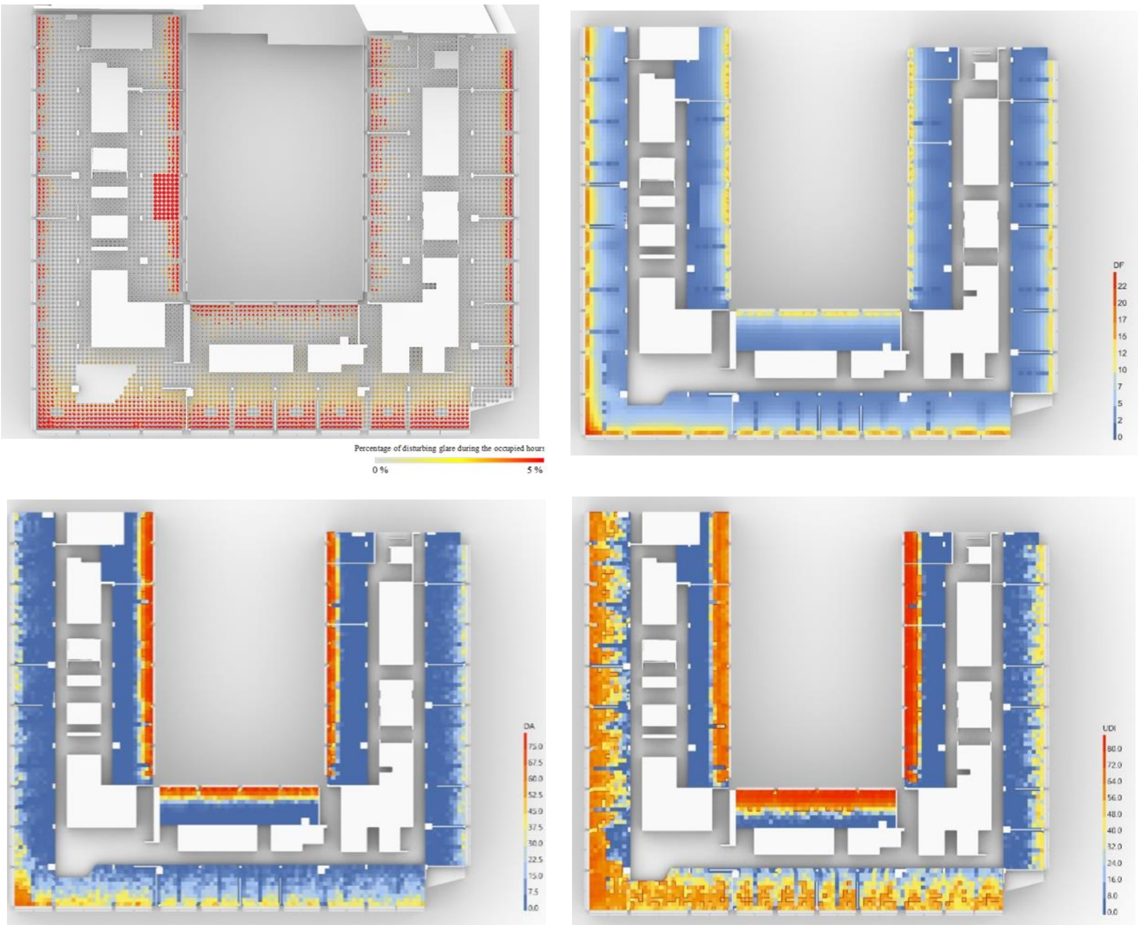

Fig. 3: Top-left to bottom-right: spatial daylight glare probability, daylight factor, daylight autonomy (DA_{300}) and useful daylight illuminance ($UDI_{300-2000}$) for the fourth floor of the case study building.

3.2 Observations from the survey

A total of 47 employees responded to the survey and filled in the lighting diary, but nine responses were discarded because wrongly filled. All responded were full-time employees who occupied the workspace for at least 30h per week. Among the 38 remaining respondents, 37 % represented employees with sitting desks adjacent to the South-East façade, 34 % to the North-West façade, and the remaining to the South-West façade. 8 % of the respondents had an individual office, 24 % shared the office with a colleague, and the remaining where in the landscape offices. Responded from the individual or two sharing office rooms had windows facing towards the courtyard, while the landscape office had windows facing the exterior. All responded had access to the manual control for at least one window in their workspace.

The survey and diary results confirmed that the occupants control solar shading primarily to avoid glare according (86 % of respondents). When glare was occasional and not persisting, the occupants first tended to adapt to the situation by moving the monitor slightly. Shadings were not operated unless it was impossible to avoid reflections on the screen after reasonable adjustments of its position. If glare persisted for longer periods, then occupants would operate the shading. Only 21 % of the recorded solar shading states included fully closed position, while shading was closed only to the extent that this protected from glare source. According to the survey, the occupants did so to keep high daylight and view out. Most of solar shading movements were recorded at the beginning and end of the day, with solar disc in the field of view for the more East and West oriented façade. Blinds were 50 % to 100% closed during the morning and at the end of a workday for 79 % and 51 % of the respondents, respectively. The shadings were open or at most 25 % closed at other times.

Occupants experiencing glare in the afternoon were likely to leave the shades in the same state until the next day morning. Almost all respondents (91 %) did not change the shading position before leaving the office at the end of a workday. Employees sitting next to the windows were twice as likely to operate the shading than other employees. Those having control over the shading system were also more satisfied than the other employees in respect to the daylight conditions and solar shading system in the space.

3.3 Development of prediction model

Since glare appeared to be the main driver for shading operation, the prediction model was based entirely on visual comfort. The model includes reflections on screens. The shading state is derived by the information provided by the survey (Fig. 4). Glare is assessed by mean of DGP with threshold DGP ≥ 0.35. Screen reflection is accounted in a simplified way, i.e., if DGP ≥ 0.45 for the field of view opposite to the screen, then there should be a high luminous source which can cause reflection on the screen. The developed prediction model accounts for the reported individual behavior, but it is of deterministic nature.

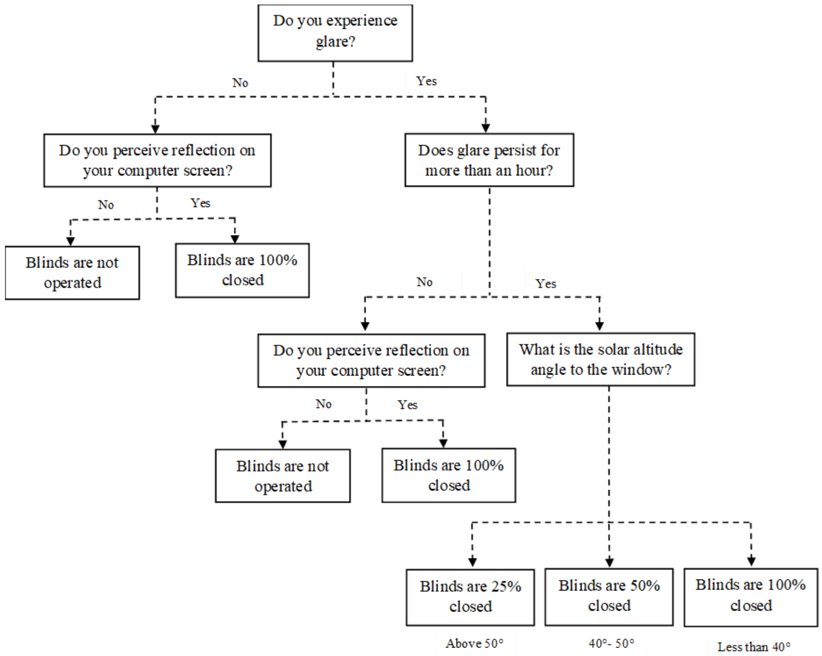

Fig. 4: The prediction model for operation of manual shades for the case study building.

When tested against the actual shade positions, 10 % of the solar shades were in a different state than the predicted position with respect to the total number of solar shades in the fourth level of the building, mainly on the South-West and North-West facades. The South-East façade towards the courtyard and the North-West façade to the exterior showed minimum to no deviation between actual and predicted position. The shading positions recorded at 13:30 had the highest deviation from the prediction model on both test days (17-19 % of difference).

3.5 Blind movements

Blind Use Frequency (BUF) and the Number of Blind Movements (NBM) were used to describe the use of blinds. BUF represents the hours in which at least one blind on the façade of the fourth floor is changed from the previous position to the new position (partly or entirely). BUF does not consider the number of shading devices that are used at a given time. NBM represents the ratio of the total number of blind movements per hour to the total number of blinds moved in the day with respect to an automated shading system.

The automated mode was much more responsive to changes in the weather conditions (Figure 5). Differences are higher during the summertime, mainly due to the irradiation set point since the prediction model is based on visual comfort only. Differences are less marked during the winter, when even the manual mode responds to low sun angles, causing glare and triggering use of shades. Similar considerations apply to NBM (Figure 6).

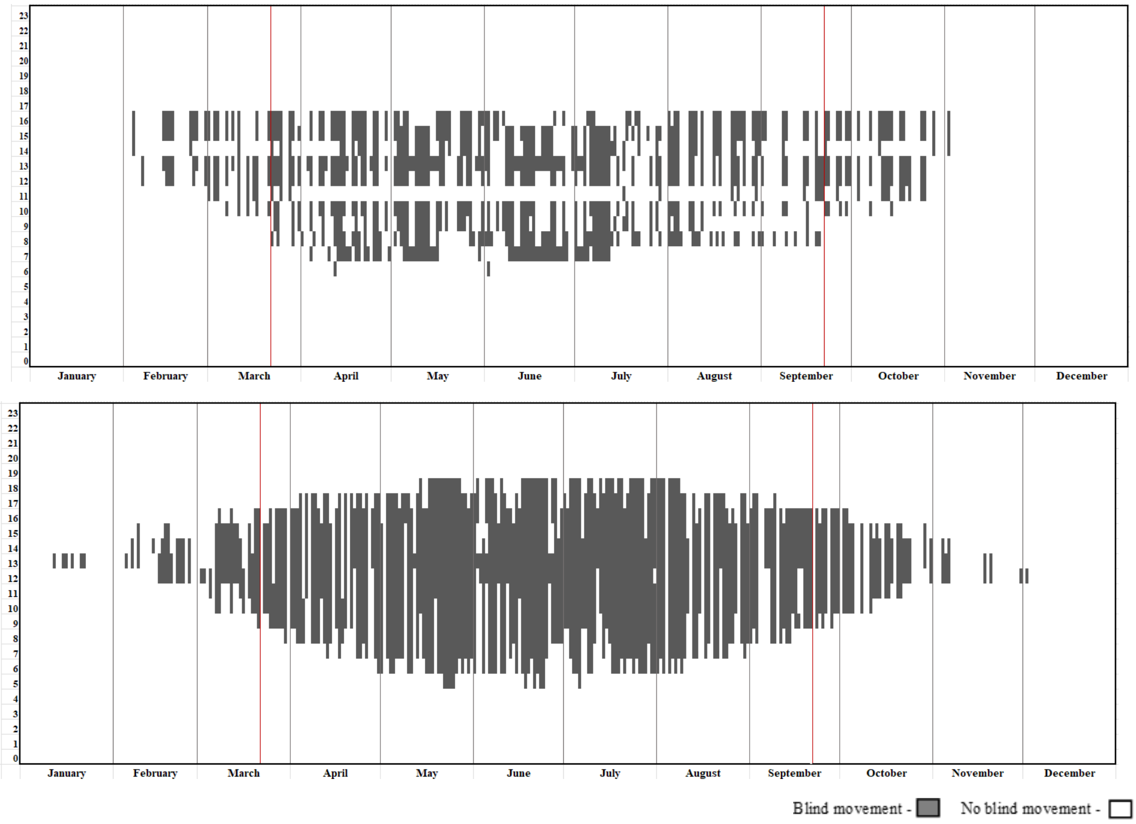

Fig. 5: BUF for the manual (above) and automated (below) modes of the solar shading. The red lines delimit the cooling period, assumed to be between the two equinoxes.

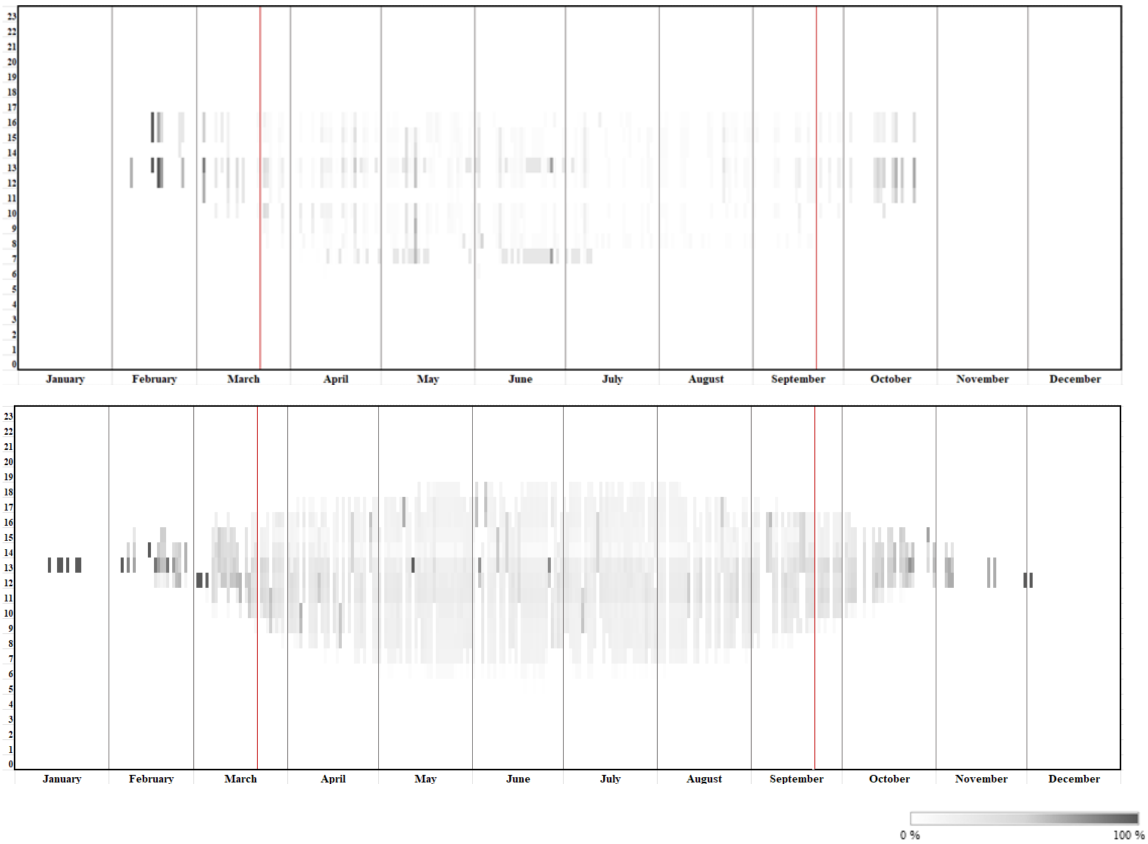

Fig. 6: NBM for the manual (above) and automated (below) modes of the solar shading. The red lines delimit the cooling period, assumed to be between the two equinoxes.

3.6 Annual solar heat gains

The annual solar heat gains for the manually operated shading system as from the prediction model were 22 % higher than that of the automated shading system, accounting for 764 kWh/m^2/year and 626 kWh/m^2/year, respectively. This is mainly explained by the unresponsiveness to solar radiation of the developed model. Winter solar gains were 9 % higher for the manually mode (118 kWh/m^2 vs 108 kWh/m^2), which is positive in energy performance perspective. Summer solar gains were 25 % higher for the manually mode (646 kWh/m^2 and 518 kWh/m^2), which is instead negative in energy performance perspective.

The prediction model failed to reduce peak loads. According to the model, only 17 % the shadings were in fully closed position during peak radiation.

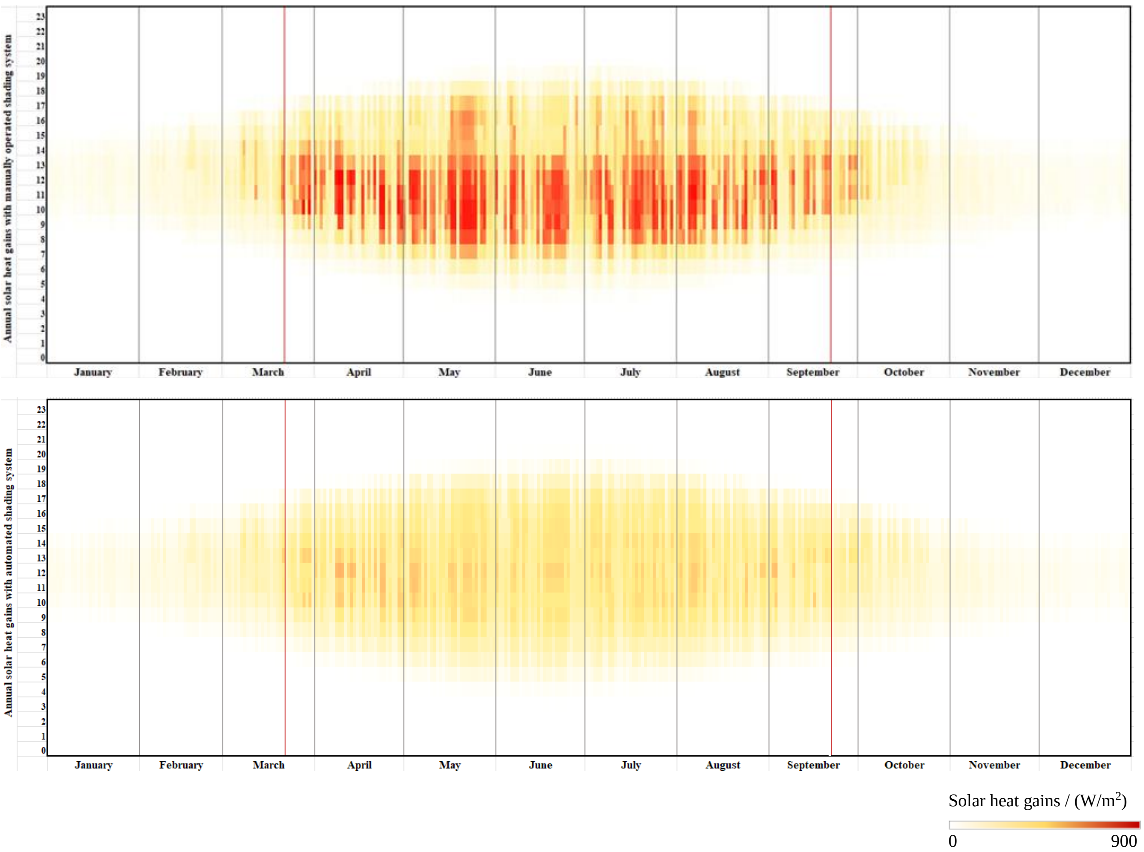

Fig. 7: Annual solar heat gains for the manual (above) and automated (below) modes.

4. Discussion and Limitations

The core of the study, which is the development of the predictive model, showed that behavior towards shading is not trivial. The survey allowed us to understand that, at least for the case study building, action depends largely on visual comfort. However, it is still questionable whether our specific prediction model would be largely or in part applicable to other case study buildings or even to the same case study building during the whole year.

In fact, the observations were carried out during the spring months, when visual discomfort is more likely to occur at north latitudes due to low sun angle, and thermal discomfort is less likely to occur due to weather conditions. Thus, the survey may have led to a model which overweighted visual discomfort and underweighted thermal discomfort. This hypothesis sounds reasonable when looking at the wide differences of BUF and NBM between the model-based manual mode and the automatic one.

During the spring months, however, the model proved reliable. This suggests that the approach for building the model - survey information combined with set-points for environmental cues – can be tested for further and extended to longer periods and situations.

The model led to higher energy use in respect to automatic shades. Such result was expected as automatic systems are explicitly designed to maximize energy savings. It is however unknown if such automatic systems would be generally appreciated by the occupants; low appreciation may lead to frequent overriding and even sabotage, as shown in other research. Also, the relatively big difference in measured solar heat gains between the two control modes – manual and automatic – might be largely explained by the model construction.

The model comes with further limitations in its current form. Among them, two main issues can be mentioned. First, screen reflection was deemed important for shading operation, but this is yet computed in an extremely simplified way, i.e., via luminance mapping of the field of view in front of the screen. Reflection can also be caused in other instances due to highly reflective material in and around the office or by neighbouring buildings which are difficult. The measure of tolerable and intolerable reflections on the monitor are also very individual. Second, and somewhat linked to the "individuality" of what is tolerable or not, the model is deterministic, since the limited number of subject and the time of observation did not allow to built probability curve that would have been useful to add a stochasticity layer to the model.

5. Conclusion

In this study, a prediction model for shade position was illustrated. The model was based on survey responses, and it used visual comfort as the only predictor for action on shading. The model was found to predict well the actual operation during three test days in spring. The following can be concluded:

- Minimizing visual discomfort was the major driving factor for the occupants to control the shading system.
- Occupants also adapt to the environmental conditions to a certain degree and delay the operation of the shading system.
- Visual discomfort and glare can be reduced significantly even when the solar shading is at a partially open/close state.
- A comparison with automatic mode of shading control revealed a better energy performance of the latter, mainly due to more automatic adjustments of shadings during summertime.
- Blind movements are significantly higher in an automated shading system when compared to a manually operated shading system.
- Occupant behavior on manually operated shading systems causes a negative impact on the building cooling load in comparison to automated shading systems.

The simplifications done in the study method limit the applicability of the results, but they still suggest a relevant impact of occupant behavior on manually operated solar shading devices.

6. Acknowledgments

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