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A low-cost framework to establish internal blind control patterns and enable simulation-based user-centric design

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ABSTRACT

The literature emphasises the important role that occupants play on the energy performance of buildings, and increasing knowledge of drivers for human-building interactions is required. However, innovative sensors or technology are not always available – especially in developing countries – and stakeholders from the building sector may struggle to reach meaningful outcomes. Therefore, we propose a low-cost framework to assess patterns of internal blind control that can be replied in different locations. It is a questionnaire-based evaluation, which infers self-reported patterns of behaviour, as well as non-physical parameters and building characteristics that influence internal blind adjustments. A case study applying the framework was conducted in Florianópolis, southern Brazil, and the results are presented. Three control patterns were identified using hierarchical cluster analysis, which provides valuable insights to estimate building energy consumption considering the influence of user behaviour in performance simulations. Also, Chi-square tests showed an association of building characteristics – solar orientation and distance between user and window – to the internal blind adjustments. This case study supports the role of user-centric design as by understanding drivers for occupant behaviour one may adapt buildings and systems to the needs or preferences of users. Along these lines, if typical patterns of behaviour, as well as main triggers for adjustments, are found, simulation-based evaluations may present to stakeholders the best options of blind properties (e.g., considering finishings or colours). Finally, this framework makes room to combine information found on field studies to published models and algorithms of internal blind control.

1. Introduction

Daylight use is a recognised strategy to promote energy savings, especially in office buildings, where occupancy occurs during the daytime; therefore, the use of daylight in office buildings reduces the energy demand for artificial lighting [1–4]. Additionally, daylight use in buildings has been associated with benefits in user productivity and health [5]. Nonetheless, office buildings require a selective use of daylight to avoid visual discomfort (e.g., glare) and excessive incident solar radiation – influencing factors for adjusting internal blinds [6], which would increase the cooling energy demand. Internal blinds are often used in office buildings to control daylight, but their adjustments depend on the active behaviour of users [7], and sometimes users tend to avoid daylight and rely on electric lighting [8]. Although control algorithms for automated internal blinds that improve the internal conditions of the spaces have been created [9,10], most of the systems in Brazilian offices are manually operated and relies on user behaviour.

Occupant behaviour is one of the driving factors of energy use in buildings, and this influence has been largely shown in the literature [11–17]. Along these lines, a literature review provided a list of influencing variables related to adjusting internal blinds; visual comfort was presented as the most frequent influencing variable, followed by thermal comfort, privacy and views of the outside [18]. The influence of visual comfort in blind control was also pointed out in different studies [19–21]. Similarly, the operation of internal blinds in office buildings was studied using mixed-mode monitoring that included photographic records and questionnaire application [22]. The monitoring results showed that dissatisfaction with the visual environment and excessive solar radiation on the work surface were the primary triggers for adjusting the internal blinds. Therefore, the literature supports that obtaining more energy-efficient buildings is dependent on the integration of technical and behavioural aspects [23]. Attempts of reducing building energy consumption based only on technical aspects result in findings of limited practical significance, as user behaviours affect the energy performance during the lifespan of the building [23].

Given the diversity of variables that affect user interactions with

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internal blinds, it is essential to monitor how the users interact with the built environment. Several studies have focused on patterns of user interactions with internal blinds [20,24,25]. In this regard, behavioural patterns were created and used in building performance simulation (BPS) [26,27]. Also, a stochastic model for blind control was developed based on the influence of solar radiation on user interactions with blinds [28]. The model was applied in co-simulation to assess the energy performance of manually operated blinds in office buildings. Finally, the influence of building characteristics on occupant behaviour using building performance simulations was also investigated [29]. Once the building characteristics impact on internal environment parameters – such as dampness [30] – it is essential to understand if the building characteristics also influence the user behaviours. This knowledge can optimise building design to decrease energy consumption, including robustness to user behaviour since the building conception [31,32].

Although much progress has been done in the field, most of the studies rely on the use of building automation systems or installation of up-to-date sensors to precisely monitor internal blind adjustments and create complex human behaviour models. However, developing countries like Brazil frequently lack this kind of data, either because most of the buildings are manually controlled or sensor installations are unfeasible in many cases due to their high price. The literature supports that consumers in developing countries place a lower value on energy-efficiency measures compared to those from developed countries [33]; thus, simple yet effective frameworks can enhance user participation in the role of energy use in buildings. Additionally, developed and developing countries present variation regarding the building sector: the former has its building stock already constructed, while the latter is still facing high levels of constructions due to social and economic development [34]. Thus, including awareness about the impact of occupant behaviour on performance of buildings during their design processes is necessary to guarantee the cleaner production of future buildings.

Therefore, in this article, a low-cost questionnaire-based framework is proposed to evaluate user interactions with internal blinds and establish human behaviour models to be included in BPS. To assess the feasibility of this approach, a case study in an office building in southern Brazil was conducted. The evaluation also explored the influence of several variables related to the building characteristics (e.g., solar orientation, distance from the user to the window, floor level) in the adjustments of internal blinds. Such a framework is aimed to improve the user-centric design of internal blind systems, as choosing the right characteristics can boost both energy performance and user satisfaction in buildings.

2. Summary of the literature related to internal blind adjustments

To have a more profound comprehension about the impact of internal blind/shade control patterns on the performance of office buildings, the literature on this topic over the last ten years (from 2009 to 2019) was reviewed. For doing so, the Scopus database was used, and a search including the following combination was done:

(blind **OR** shade) **AND** ((occupant **OR** user) **AND** behavio*) **AND** office

With this search, 54 documents were found. From the literature review, two main aspects related to the topic were explored: monitoring and modelling approaches related to adjustments of internal blinds/shades in offices. Therefore, the following subsections show outcomes on both of them, as well as a conclusion regarding these aspects supporting the need of including simple yet effective evaluations of internal blind adjustments in office buildings.

2.1. Monitoring approaches

According to a critical review of studies on adjustments of shades in offices, the three most used techniques for monitoring are time-lapse photography of façades, sensors to measure shade position and walk-throughs to observe shade position in the buildings [18]. However, the literature also supports using questionnaires to assess self-reported patterns of behaviour [27], to ask the status of the internal blinds/shades similarly to personal diaries [35], or to study subjective aspects like social norms in shared spaces that affect internal blind adjustments [36,37]. When occupants are asked to report the status of the internal blinds during a given timeframe, researchers may require only right-in-time reports instead of repeatedly asking throughout a day [38]. This strategy may minimise bothering levels compared to asking for occupants' responses on an hourly basis, as found in another piece of research [39].

Regarding the use of photographs, different approaches (indoor photos [40] or façade photos [41,42]), time intervals (every 30 min [41], every hour [28], every 2 h [43,44]) and combination with other methods were found (e.g., with questionnaires to assess subjective responses [22], with monitoring data from sensors integrated with automation system [41,45], with exterior environmental conditions [42,43]).

As there is no rule to conduct studies on this topic, researchers should use some past experiences, either from the literature or from their work, to design a feasible experiment that may improve the performance of buildings. Therefore, this literature review found that the monitoring approaches are highly conditioned to choices made by those who are responsible for the studies. In general, long-term monitoring campaigns have been reported in the literature, and those outcomes are highly important to the field [25]. However, it is vital to consider that long-term monitorings are time and resource consuming, and even being useful and providing extensive outcomes, should not be considered the only way to assess the patterns of internal blind adjustments. Many pieces of research did not conduct any monitoring at all; instead, they relied on previously-published monitoring and modelling reports to conduct comparative analysis and also contributed to the field [46–48].

Besides real-life scenarios, the literature also supports studies conducted in immersive environments [49,50] and in semi-controlled environments to study occupant behaviour [51]. Along these lines, such controlled experiments allow testing different characteristics and their influence on the role of building performance; and results support that when occupants are provided with semi-automated shades, they are more likely to use daylight in offices [52]. Similarly, by providing easier-to-access controls, automated roller shades may be adjusted in ways that improve daylight use [53].

2.2. Modelling approaches

Several modelling approaches may be used to represent occupant behaviour in buildings, and a recent literature review synthesised them in three main groups: adaptive behaviour models, non-adaptive behaviour models, and occupancy models [54]. Regarding internal blinds or shades models, they can be either adaptive (e.g., driven by indoor conditions, like solar radiation) or non-adaptive (e.g., driven by factors mainly linked to the time, like opening blinds when arriving at the office).

As the role of modelling occupant behaviour, including shading use, has become more complex lately, several methods can be chosen to be included in BPS. Among modelling approaches used, the most common strategies include stochastic modelling [22,25,28,41,55], Bayesian approaches [56], agent-based modelling [35,57,58], artificial neural network [38], cluster-based models [27], rule-based models [46], as well as "ideal models" that consider the best situations to open/close internal blinds to improve building performance [59]. However, the literature supports that the complexity level of the modelling