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An integrated thermal and lighting simulation tool to support the design process of complex fenestration systems for office buildings

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HIGHLIGHTS

- *mkSchedule* is an effective tool for supporting the early building design stages.
- Integrated thermal and lighting simulations are performed efficiently.
- Controlled external shading devices provide comfort and energy efficiency.
- The maximum incident irradiance for comfort and energy efficiency is determined.

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ABSTRACT

Office buildings are greatly affected by solar heat gain and daylight transmission through fenestrations. External shading devices control the solar radiation transmission, thus they significantly influence building performance because of improving energy efficiency and visual comfort. Automated control systems for external shading devices to simultaneously control solar heat gain and indoor illuminance can minimize the energy use and provide visual comfort. To minimize the total energy consumption, building designers need the support of building performance simulation tools that can integrate the thermal and lighting simulations, such as *mkSchedule*. The main objective of this paper is to demonstrate the use of *mkSchedule* as a tool for supporting the decision-making process in the early building design stages using a case study of an office space with two different external and movable complex fenestration systems (CFSs) and controlled dimmed luminaires in four cities. The CFSs are controlled by the irradiance on the façade, and *mkSchedule* is used to determine the maximum allowable irradiance that minimizes the energy consumption while meeting the visual comfort criteria. The four studied cities are Montreal, Canada; Boulder, USA; Miami, USA; and Santiago, Chile. Two external shading devices are evaluated, a set of external perforated curved louvers and a set of venetian blinds. For each case, the visual comfort was assessed based on the spatial daylight autonomy (sDA) and the annual sunlight exposure (ASE) according to the Illuminating Engineering Society (IES) standard; whereas, the building energy performance was determined in terms of the sum of heating, cooling and lighting energy consumption. For the venetian blinds, the maximum incident irradiance threshold varied between 530 W/m^2 and 610 W/m^2; while this threshold varied between 290 W/m^2 and 350 W/m^2 for the louvers. This study demonstrates that *mkSchedule* is an effective tool for determining the performance of different CFSs in the early building design stages considering visual comfort criteria and building energy performance, thus it provides information not only to choose among different alternatives of CFSs and control algorithms, but also to set the main parameters of the control algorithm.

1. Introduction

Buildings account for approximately 32% of the world's total annual energy consumption in 2010, 33% of the greenhouse gas emissions and people spent over 90% working or living inside

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buildings, which has led to intense and varied research worldwide to improve both visual comfort and energy efficiency of buildings [1,2]. Both retrofitting of existing buildings and construction of new buildings represent opportunities to design, build and operate high performance buildings for reducing the energy consumption and providing acceptable indoor environmental quality [3].

The energy use for lighting, heating and cooling directly relates to the building envelope design, internal heat gains and climate [4–6]. Office buildings with highly glazed facades are widespread worldwide independent of the climate. These buildings usually have unsatisfactory occupant's visual comfort and high cooling and lighting energy consumption [7,8], that is mainly explained by the large amount of solar radiation transmitted through the glazing façades into the indoor space [5,9–13].

To increase the thermal and lighting performance of buildings, external solar protection systems have been widely used including a large variety of shading devices such as blinds, louvers, screens, meshes, etc. These devices are made of different materials (e.g. fabric, metal) and geometries, while they are fixed or automatically/-manually controlled. Some of these shading systems are complex fenestration systems (CFSs), which consist of a non-specular solar protection device, such as louvers or venetian blinds installed on a glazed façade [14–24].

Literature review evidences that many studies have been conducted to determine the effectiveness of external CFSs on controlling solar heat gains and daylighting, which ranges from experimental works to optimization via simulations. For instance, [10] conducted a monitoring campaign in 3 office buildings in Santiago, Chile, which has a semiarid climate and high solar radiation during the cooling season. This study found that due to inappropriate designs, the fixed external CFSs in two cases did not offer adequate solar control, allowing the incidence of direct solar radiation on the indoor work plane. The automatically controlled external solar shading device (rollers) that was used on the west-facing façade of a building performed significantly better than the fixed systems. Other studies have focused on evaluating different shading systems and different control algorithms. For example, [25] evaluated a combination of external (venetian blinds) and internal (roller, Retrolux blind) shading systems in two different climates. [17] evaluated different control strategies (cut-off angle, daylight-redirecting and two different glare controls) for venetian blinds of an office space. The evaluation of the control strategies was based on daylighting transmission, lighting energy consumption and occupant's visual comfort. [26] studied three slat's tilt angles of external venetian blinds (0°, 15° and 30°) assuming manual control of them. Other studies have focused on finding optimal solution of the CFS. [22] investigated twelve different coplanar shades with different geometries, material properties and cut-off angles in the climates of the San Francisco Bay Area and Southern California. They identified an optimum slat angle for each city and found that all the exterior slat shades reduced the energy consumption, while some cases were better for daylighting control. Similarly, [27] integrated daylighting and energy performance with genetic algorithms and artificial neural network models to optimize an office with controlled indoor venetian blinds and dimmed lights, which was located in Seoul (Korea). They found that the optimization methods implemented allow energy savings up to 13.7% for the evaluated period of three months. Most recently, [23] optimized curved and perforated louvers in four different cities balancing energy consumption and visual comfort. They found that the CFS optimized solely based on total energy consumption does not meet the visual comfort metrics. Nevertheless, including visual comfort metrics in the cost function enables to provide visual comfort and reduce the building's energy consumption. Finally, a new approach is emerging that focuses on defining the activation threshold or other parameters of the CFS's control strategy. A unique study of [28] studied the appropriate irradiance that activates external blinds controlled by irradiance based on visual comfort and lighting energy consumption in different climates. Below the activation threshold the blinds are open while above this value the blinds are completely close. They found the activation threshold varied between 100 and 200 W/m^2 according to the climate and window orientation as expected. However, the optimal slat angle of the venetian blinds was found to be highly dependent of the irradiance activation threshold. This study is the only one that have focused on establishing a control parameter of the CFS's control algorithm based on its impact on the occupant's visual comfort and building energy efficiency.

Literature review shows that certain CFSs performs better in terms of controlling daylighting for occupant's visual comfort and controlling solar heat gains for building energy efficiency. However, the building's thermal and lighting behavior needs to be evaluated at the early stages of the architectural design process. In this phase, designers have to take decisions among a large number of design alternatives towards more optimal designs. Since the end cost, building performance (e.g. energy efficiency) and occupants' comfort (e.g., visual comfort) are strongly influenced by the decisions taken in the early design stage, the greatest opportunities to achieve high performance buildings occurs in this phase of the design process [29,30]. Here, building performance simulation (BPS) tools can play a crucial role providing accurate and timely information for decision-makers [31]. However, [32] point that advanced BPS tools are not easily introduced at this stage of the building design, while very few BPS software are used in automated building optimization processes. On the other hand, simpler tools increase the risks of inaccurate results.

Since CFSs affect the HVAC and lighting energy consumption and the daylighting provision to the indoor environment, integrated thermal and lighting simulation tools are required to support the making-decision process about the fenestration alternatives at early design stages of buildings [14]. Table 1 shows the main efforts to integrate thermal and lighting simulation software. It is evident that most of these tools have integrated or used state-of-the art thermal and lighting simulations software such ESP-r [33] or EnergyPlus [34] for energy simulations and Radiance [35] or DAYSIM [36] for lighting simulations. Table 1 evidences most of the integrated simulation tools have limitations that affect their accuracy. However, the high computing time and lack of flexibility to evaluate different alternatives of the building and fenestration system diminishes the potential of these BPS tools to be used in early design stages of buildings. Fener [18] and *mkSchedule* [37] show very similar characteristics but the latest allow simulating multiple zone buildings.*mkSchedule* is a time-efficient tool that was recently developed. This tool performs integrated thermal and lighting simulations for fixed and movable CFSs using the three-phase method. *mkSchedule* uses Radiance for the lighting domain and EnergyPlus for the thermal domain. Using a simple case study, [37] demonstrated that *mkSchedule* integrates Groundhog (a SketchUp plug-in), Radiance and EnergyPlus, producing results within a short period of time and allowing flexibility to incorporate different design alternatives. As consequence, this tool can be used in the early stages of the building design process to evaluate the impact of different shading systems and control strategies and to determine the appropriate thresholds and parameters of the control strategies.

Therefore, the main objective of this paper is to demonstrate the use of *mkSched*ule as a tool to support the decision-making process in the early building design stages through a complex case study of an office space. Two different external movable shading devices of CFS and controlled dimmed luminaires are evaluated in four cities (i.e., Montreal, Canada; Boulder, USA; Miami, USA; and Santiago, Chile). The CFSs are controlled by the irradiance on the façade,