Energy Use Sensitivity Analysis of Sensor Placement in Small Office Buildings with Dynamic Shading and Lighting

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ABSTRACT

The main energy end uses in commercial buildings include cooling, heating, and lighting. These energy consuming systems, however, can be substantially impacted by environmental parameters and sensor inputs when a building is being dynamically controlled. This study aims to conduct a sensitivity analysis on the energy consumption of a small commercial office building with an integrated control system, including automated shade devices and dimmable lighting. Previous studies have focused on sensitivity of automated shades energy impacts, based on glare level, solar irradiation, available daylighting and solar penetration; others have assessed the sensitivity of dimmable lighting on energy use. The focus of this study is to assess the impact of adjusting illuminance sensor location, and sensor rotation (towards or away from the exterior windows), for small office buildings with integrated shading and lighting controls in different ASHRAE climate zones.

INTRODUCTION

Many technologies have been deployed to advance building control systems, such as automated shades, dimmable lighting fixtures, and programmed thermostats. Many of these technologies rely on various sensors, such as those that detect air quality, daylight, humidity, occupancy, and temperature, for use in controlling smart buildings. (Sinopoli 2009) The output values obtained by these sensors are meant to represent the indoor environmental conditions experienced by occupants, and are used to control building system components. However there has been limited study and guidance on appropriate placement of these various sensors within a building, including how sensitive the controls and thus energy use of the building is to sensor placement. Conducting sensor sensitivity analysis of the designed control system will help to understand how impactful this placement is on performance, and can help to optimize the overall controls to achieve better energy consumption and performance. Given that buildings are designed and perform differently in different climate zones, (cold climate zones have higher heating loads, and hot climate zones have higher cooling loads) (Shen and Tzempelikos 2012; Cygańska and Kludacz-Alessandri 2021; Shen and Hong 2009), this study also assesses these impacts and sensitivities in different climate zones.

METHODOLOGY

Modeling was completed following a three-step process as shown in Figure 1. (a) The first step was to develop the zone-level daylight modeling using RADIANCE (2022; Subramaniam 2017) to simulate illuminance values. The daylighting model used various inputs, including zone geometry, Bidirectional Scattering Distribution Function (BSDF) files for roller shades and the window, sensor locations at the two sensor locations at vertical eye-level, workplane sensor locations, and weather data as an input to generate illuminance values. (b) The second step was selection of shade and lighting level using the illuminance values generated from step (a). An appropriate shade position and lighting level was selected based to satisfy occupants' visual comfort requirements for a combination of various control modes. For instance, the shades are closed in increments of 10 % of until the vertical illuminance values are lower than 2000 lux (185.8 fc). Further, at the selected shade position, workplace illuminance values are checked to evaluate if artificial lighting is required. If not, the lights are dimmed to maintain a workplace illuminance value of 375 lux (34.8 fc). (c) The third step updated the selected shading and lighting level to the energy model. Both the Baseline (modified 2004 DOE prototype small office buildings (U.S. DOE, 2022)) and updated Energy Efficiency model (including shading and lighting control) were run to compare differences in energy consumption, thermal and visual comfort. The Baseline model was developed using the Reinhart's (2001) manual control shade model where the shades are raised up in the morning and closed (remain closed) when direct sunlight hits the occupants with direct solar irradiance higher than 50 W/m^2 using the Lansing, MI weather file. The Energy Efficiency

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model includes dynamic shade positions and lighting levels, as well as LED fixture updates (LED retrofit factor of 0.64 switching from fluorescent to LED light fixtures) and task tunning lighting control using a factor of 0.585 (DLC and NEEA 2020; Williams et al. 2012).

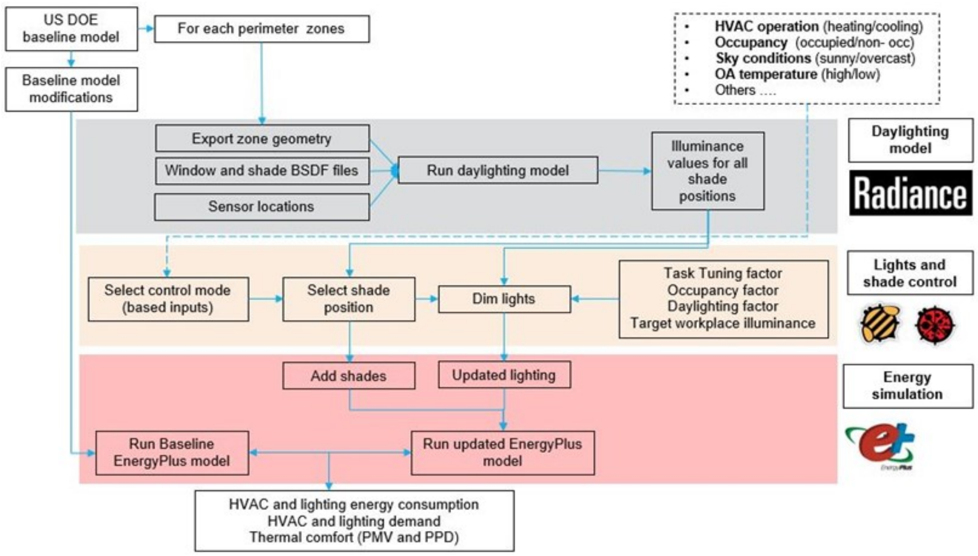

Figure 1 Three-step model simulation workflow

Within the model, illuminance sensors were placed 1.6m (5.2ft) away from the window in each perimeter zone. This location served as the baseline case for the sensor location sensitivity analysis. The horizontal workplane sensors were placed at a height of 0.76m (2.5ft), and the vertical illuminance sensor was placed at a height of 1.2m (3.9ft). These heights are based on values used in other research, including the Daylight Metrics Project (2008), Kunwar et al. (2020), as well as other studies (Shen and Tzempelikos 2012; Wienold 2009). To evaluate sensitivity, the sensor location (both workplane and vertical illuminance sensors) was increased incrementally from 1.6m (5.2ft), 2.4m (7.9ft), 3.6m (11.8ft), to 4.9m (16.1ft) away from the exterior window.

The illuminance sensors are placed on a horizontal work plane (facing towards the ceiling) and vertical sitting eye height level (facing horizontally towards the window). To evaluate the sensitivity of the model results to the orientation of the vertical sensors, first model performance was evaluated with the vertical illuminance sensor facing the window to mimic occupants facing the window (worst case scenario). The vertical illuminance sensor was then rotated counterclockwise 90 degrees such that the sensor is facing the side window. This mimics a scenario where occupants are facing a side wall, similar to what is used in some glare studies. (Shen and Tzempelikos 2012; Wienold 2009; Park et al. 2011)

Next ASHRAE climate zones were selected for evaluating building performance and sensitivity in different geographic locations. For each location, the corresponding prototype building model was used (U.S. DOE, 2022). TMY3 files (EnergyPlus, 2022) were used, including for ASHRAE CZ 2A (Tampa, FL), 2B (Tucson, AZ), 4A (New York, NY), 4B (Albuquerque, NM), 5A (Lansing, MI), 6A (Rochester, MN), and 6B (Great Falls, MO).

RESULTS

The simulated annual energy loads for a small office building located in ASHRAE Climate Zone 5A using Energy Efficiency model are shown in Figure 2. This figure shows the annual cooling, heating and lighting energy use for building models where the veritical and horizontal illuminance sensor placements are adjusted. The simulated annual loads results are shown in Figure 3. As an example of the notation, 2A is the Baseline model, and 2A' is the Energy Efficiency model.

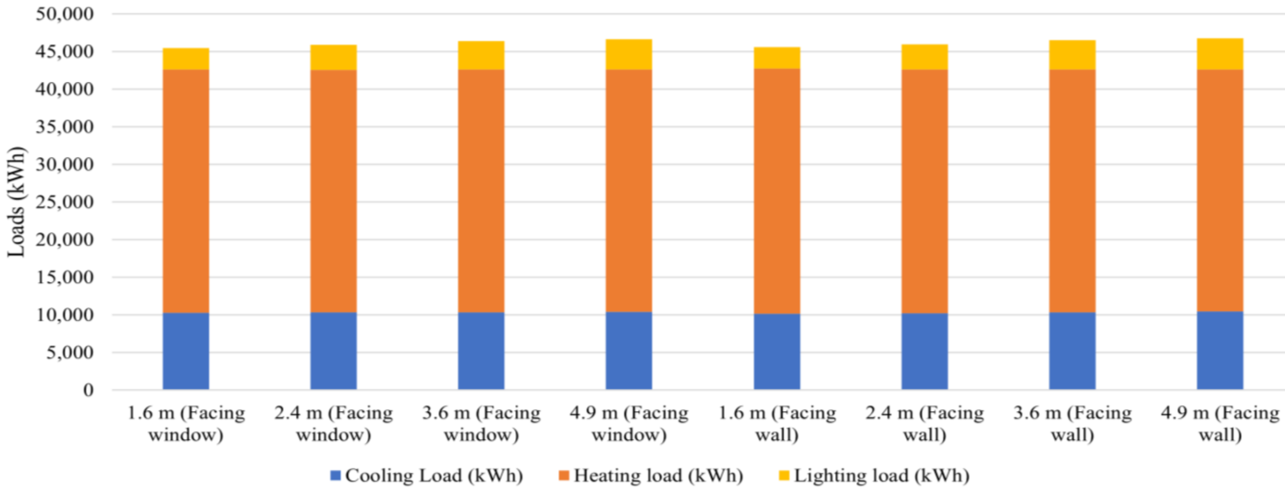

Figure 2 Energy Efficiency model annual results for different sensor locations and rotations *(Note: distance provided is the distance between the sensor location and the exterior window)*

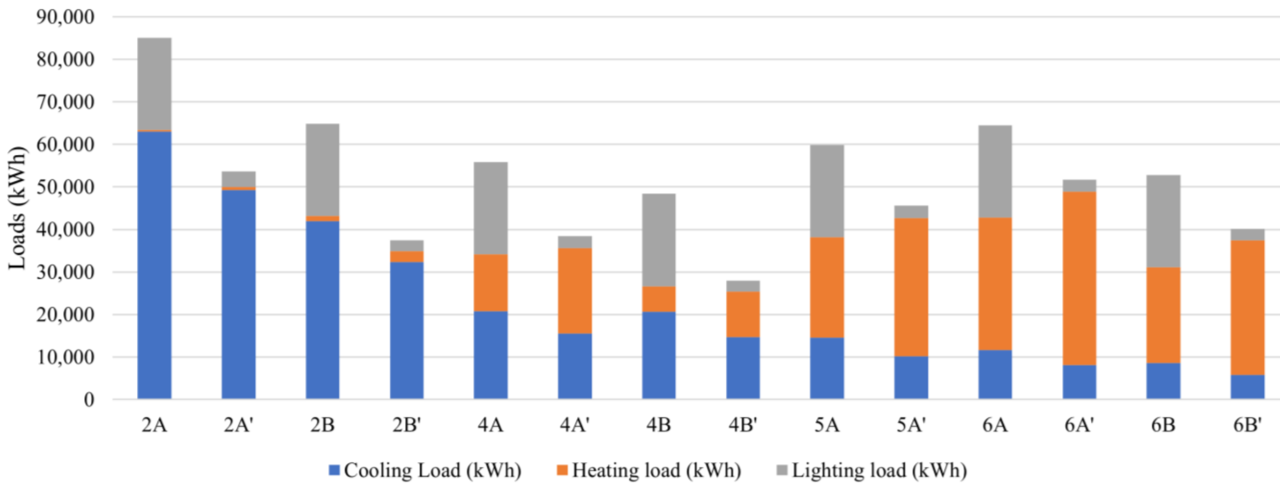

Figure 3 Baseline model and Energy Efficiency model annual results across ASHRAE climate zones (e.g. *2A* is the Baseline model in ASHRAE CZ 2A, and *2A'* is the Energy Efficiency model in CZ 2A)

CONCLUSIONS

The sensitivity of annual combined lighting and cooling energy use to sensor distances from the exterior windows and sensor rotation angle are approximately 4-12% and <1%, respectively, when evaluated using a prototypical small office building at Climate Zone 5A. There is a 4% increase in annual consumption when the sensor distance from the window is increased from 1.6m (5.2ft) to 2.4m (7.9ft), and a 12% increase when this distance is increase from 1.6m (5.2ft) and 4.9m (16.1ft) from the window. When comparing performance across climate zones, energy savings originates more from lighting for colder climate zones whereas for hotter climate zones energy saving is achieved more from a combination of cooling and lighting savings. There is an increase in heating energy (due to decrease in radiant fraction of light entering the space). However, overall, there is a net decrease of total energy (cooling, heating, and lighting), ranging from 19 - 41% (minimum is for CZ 6A; maximum is for CZ 2B) for a prototypical small office building.

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