Energy and demand saving potential due to integrated HVAC, lighting and shading controls in small office building

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ABSTRACT

With commercial and residential buildings accounting for approximately 40% of the energy and 70% of the electricity consumption in the United States, there are substantial opportunities to improve energy efficiency in these buildings. Similarly, buildings also account for the large majority of electricity demand, particularly during peak use hours. As the electric grid becomes increasingly supported by renewable energy, buildings are ideal for supporting demand-side management, allowing for the electricity demand to meet the variable levels of electricity supply. Integrated controls of various building energy system components, including HVAC (Heating Ventilation and Air Conditioning), lighting, and shading devices, combined with advanced sensor and control technologies, can help to optimize system operations. This research aims to study the impact of integrated HVAC, lighting, and shading device controls, to estimate energy and demand saving in typical small office buildings in the U.S. This is achieved through a multi-step modeling process, including daylight simulation using Radiance to evaluate available daylight for each zone, then EnergyPlus to develop and implement various controls and estimate energy and demand savings using the Radiance results as input. The result of this work provides insights for a variety of stakeholders in the building, utility and grid operator industries and quantifies the potential benefit of integrated systems.

INTRODUCTION

With rise in climate change concerns, there is need to reduce greenhouse gas emissions. In the United States, residential and commercial buildings are responsible for approximately 70% of the electricity consumption (U.S. EIA 2019), with approximately 60% of that electricity generation from greenhouse gas (GHG)-producing fossil fuels in 2020 (U.S. EIA 2021). Thus, there is a significant need to improve energy efficiency of buildings, as major energy consumers, in order to reduce energy consumption. Further, across the U.S., 21% of the electricity generation is due to renewable sources such as such as solar and wind which can be highly variable. The electricity generation from to solar and wind sources is projected to rise to nearly 47% of the generation mix in 2050 (U.S. EIA 2021). Thus, to address the variability in generation due to solar and wind generation now and in future, buildings loads can be used for demand-side management and load flexibility. Building load flexibility refers to the ability of building energy consuming systems, lighting, HVAC or others, to increase or decrease their electricity demands based on grid requirements.

One way to achieve both energy efficiency and demand flexibility improvements is by integrating multiple building energy system components such as HVAC, lighting, and building envelope components with advanced sensor and control technologies, to optimize system operations. Various studies have developed control strategies for automated lighting and shading controls to reduce energy use, considering various factors such as glare and solar irradiance to avoid occupant discomfort (Kunwar et al. 2019, Tzempelikos and Shen 2013), and occupant-based sensing to reduce HVAC loads by optimizing the heat gain through windows during non-occupied conditions for summer and winter seasons (Shen et al. 2014). Shen et al. (2014) also further suggested shading operational adjustments during the night to minimize heat loss through windows. Studies (Kunwar et al. 2019, Shen and Tzempelikos 2012) have reported a reduction of 16%-26% for cooling energy and 52%-77% for lighting energy consumption due to the use of automated shades as compared to a baseline case of no shading or lighting control.

Various other studies have also focused on the demand flexibility using building loads such as lighting and shading. A demand response (DR) study published by Lawrence Berkeley National Laboratory (LBNL) and Natural Works (Lee et al. 2007), monitored system energy performance at the Times Company in New York City, and estimated potential peak demand reduction from automated shading using EnergyPlus-based building energy simulation. Lighting represents a sizeable opportunity since it comprises 10-15% of the connected load at any given moment, and can generally be reduced by up to 20-25% without causing visual discomfort (Newsham and Birt 2010). In addition, lighting can be nearly instantaneously reduced, enabling the possibility of its use for frequency response type of flexibility services. Lighting loads in commercial buildings are further generally dependent on the space type (e.g. open office, library, surgery rooms), the lighting schedule, and the lighting efficiency. Therefore, lighting loads in buildings have consistent use patterns and that, coupled with shading devices, can be used effectively for demand reduction.

The recommended lighting level for an office space per the IES Lighting Handbook (2011) is 300 lux at the work plane level. However, various studies suggest that it is acceptable to reduce the lighting levels by a certain percent from the initial lighting level without occupants detecting it (i.e. “detectable” level) or without it causing any significant visual discomfort (i.e. “acceptable” level). For instance, Tenner et al. (1997) suggests that a reduction of 13% from an initial base illuminance value of 830 lux is acceptable. Similarly, two other studies (Akashi and Neches 2004, Kryszczuk and Boyce 2002) suggest that a reduction of 17% and 15-25%, respectively, from the initial base illuminance value of 1095 lux and 500 lux, is barely detectable. Further, Hu et al. (2016) suggest reduction around 17.8 to 19.1% from the baseline values is acceptable for base illuminance lower than 500 lux. Thus, the target level of 240 lux, which is 20 % lower than 300 lux is considered acceptable during demand response events in this study.

However, there are various challenges to expanding the use of these integrated controls for new and existing buildings. The initial cost of integration of such systems can be a barrier for some; in other scenarios, building owners are looking to use systems with a history of successful use and performance, thus limited pilot studies and data assessing energy and/or demand savings potential can also be barriers to adoption. This study thus focuses on building an integrated energy and daylighting model as a framework to analyze the potential impact of these technologies on energy saving and demand flexibility potential. The study combines these factors such as time of day, occupancy, and sky conditions to develop a preliminary control strategy for both heating and cooling condition through the year.

Office buildings are the most common type of commercial building in the United States (U.S. EIA 2012). In addition, over 50% of the commercial buildings are smaller than 465 m² (U.S. EIA 2012), and thus generally considered “small” office buildings. Therefore, this study uses the U.S. DOE Commercial Prototype Building model (U.S. DOE 2020) for a small office building as the baseline model for the preliminary analysis. The ASHRAE 90.1-2004 version was chosen of the available models, as various parameters such as lighting power density (LPD), HVAC system efficiencies and insulation characteristics resemble a typically existing office building based on recent field study results. This study used the baseline model for daylighting and energy simulation for various control modes to report both energy savings and demand flexibility potential for the south facing zone using an integrated control strategy with automated shading and lighting for climate zone 5A (Lansing, MI). The south facing zone is chosen as it generally has the greatest solar loads of the four orientations.

METHODOLOGY

Three model types

For comparison of the impact of integrated controls, this study considered three scenarios, including, a (1) *Baseline* model, which is a modified U.S. DOE Commercial Prototype small office building. Manually controlled shades were added to baseline model based on Reinhart and Voss’s model (2003), where the shades are opened by occupants each morning and are only closed (and remain closed throughout the day) if direct sunlight hits the occupants with direct solar irradiance higher than 50 W/m^2; an (2) *Energy Savings* model and a (3) *Demand Response* model which use the baseline building, from which modifications were made to add smart building technologies, including dynamic shading and automated lighting. The *Energy Savings* scenario represents the use of the technologies under normal operation without any demand response and the results are reported as energy savings in (kWh); the *Demand Response* scenario represents building operations during a demand response event, the results of which are reported in demand reduction (kW).

Overall modeling workflow

The modeling workflow follows a three-step process as shown in Figure 1. The steps summarized herein are discussed in detail in later sections. The first step (a) is zone-level daylight modeling using RADINACE (Version 5.2.2, 2021). This daylighting model uses various inputs such as zone geometry, Bidirectional Scattering Distribution Function (BSDF) files for roller shades, and the window, sensor locations and weather data as an input to generate illuminance values at two sensor locations. The second step (b) is the selection of shading height and lighting levels using the illuminance values generated from (a). The appropriate shade position and lighting level are selected to satisfy occupant visual comfort requirements for a combination of various control modes in Table 1 and 2. The third step (c) updates the selected shading and lighting level in the baseline energy model. Both the baseline and updated model are then run to compare differences in energy consumption, and demand response potential.

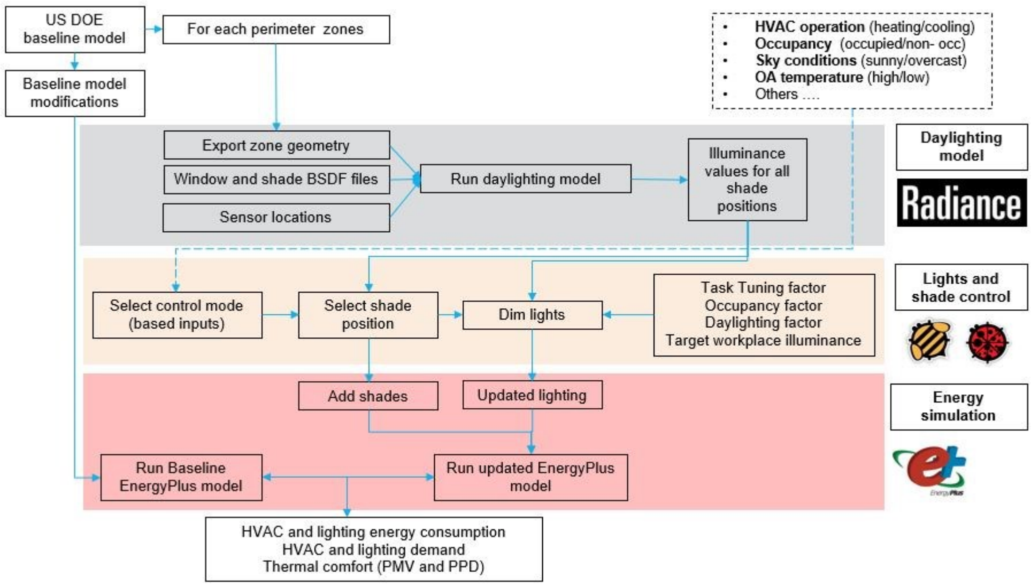

Figure 1. Daylighting modeling, Shade control and selection, and Energy simulation: Three-stage workflow

Daylighting model

RADIANCE, using a 3-phase matrix method, was used for daylight simulation (McNeil 2013). The building geometry is taken from ASHRAE 90.1-2004 Small Office Commercial Prototype building model. Two illuminance sensors both placed 1.6 meters away from window, the work plane sensor was placed at the height of 0.76 m from the floor (facing up) and vertical sensor was placed at 1.2 m above the floor (facing towards window). As an initial assumption, a demand response event was assumed for the period of 2 pm to 5 pm. We note that DR event times can vary by climate region and grid load dynamics; this choice of a DR period was chosen for this study as late afternoon time periods for DR events are common for many regions of the U.S.

Shading and lighting control model

The output from the RADIANCE simulations were then used as an input to select an appropriate shade position and lighting level in EnergyPlus based on control modes. The control modes used for this study are based on variables including HVAC operational mode (heating/cooling), time of day (day/night), occupancy (occupied/unoccupied), solar irradiance (sunny/overcast), and demand response period (DR/non-DR) (Kunwar et al. 2019, Jain and Grag 2018, Shen et al. 2014). For this study, the solar irradiance was considered as sunny when higher than 150 W/m^2 (Kunwar et al. 2019). All control variables were evaluated at an hourly level, and later collectively used to determine the control modes shown in Table 1.

Table 1. Control modes based on input variables

Control mode index	**Variables**				
	Cooling/Heating	**Day/ Night**	**Occupied/Non-Occupied**	**Sunny/ Overcast**	**With-DR/ No-DR**
Mode #1	Cooling	Night	Non-Occupied	--	--
Mode #2	Cooling	Night	Occupied	--	--
Mode #3	Cooling	Day	Non-Occupied	--	--
Mode #4	Cooling	Day	Occupied	Overcast	No-DR
Mode #5	Cooling	Day	Occupied	Overcast	With-DR
Mode #6	Cooling	Day	Occupied	Sunny	No-DR
Mode #7	Cooling	Day	Occupied	Sunny	With-DR
Mode #8	Heating	Night	Non-Occupied	--	--
Mode #9	Heating	Night	Occupied	--	--
Mode #10	Heating	Day	Non-Occupied	--	--
Mode #11	Heating	Day	Occupied	Overcast	No-DR
Mode #12	Heating	Day	Occupied	Sunny	With-DR

Based on the control modes, the shading positions and the lighting levels were selected based on Table 2. First, the shade position was selected to limit the vertical illuminance value to 2000 lux for the *Energy Savings* mode and 1800 lux for the *Demand Response* mode (Kunwar et al. 2019). For the selected shade position, a lighting level was selected such that the target work plane illuminance is as per table 2.

Table 2. Shade and lighting control strategies based on control modes

Control mode index	**Shade control operation**	**Target vertical illuminance**	**Lighting control operation**	**Target work-plane illuminance (daylight + artificial)**
Mode #1	Fully open shades	--	Switch off lights	--
Mode #2	Fully open shades	--	Limit to target	300 lux
Mode #3	Fully close shades	--	Switch off lights	--
Mode #4	Range (full open, full close)	2000 lux	Limit to target	300 lux
Mode #5	Range (full open, full close)	1800 lux	Limit to target	240 lux
Mode #6	Range (WPP, full close)	2000 lux	Limit to target	300 lux
Mode #7	Range (WPP, full close)	1800 lux	Limit to target	240 lux
Mode #8	Fully close shades	--	Switch off lights	--
Mode #9	Fully close shades	--	Limit to target	300 lux
Mode #10	Fully open shades	--	Switch off lights	--
Mode #11	Range (full open, full close)	2000 lux	Limit to target	300 lux
Mode #12	Range (WPP, full close)	2000 lux	Limit to target	300 lux

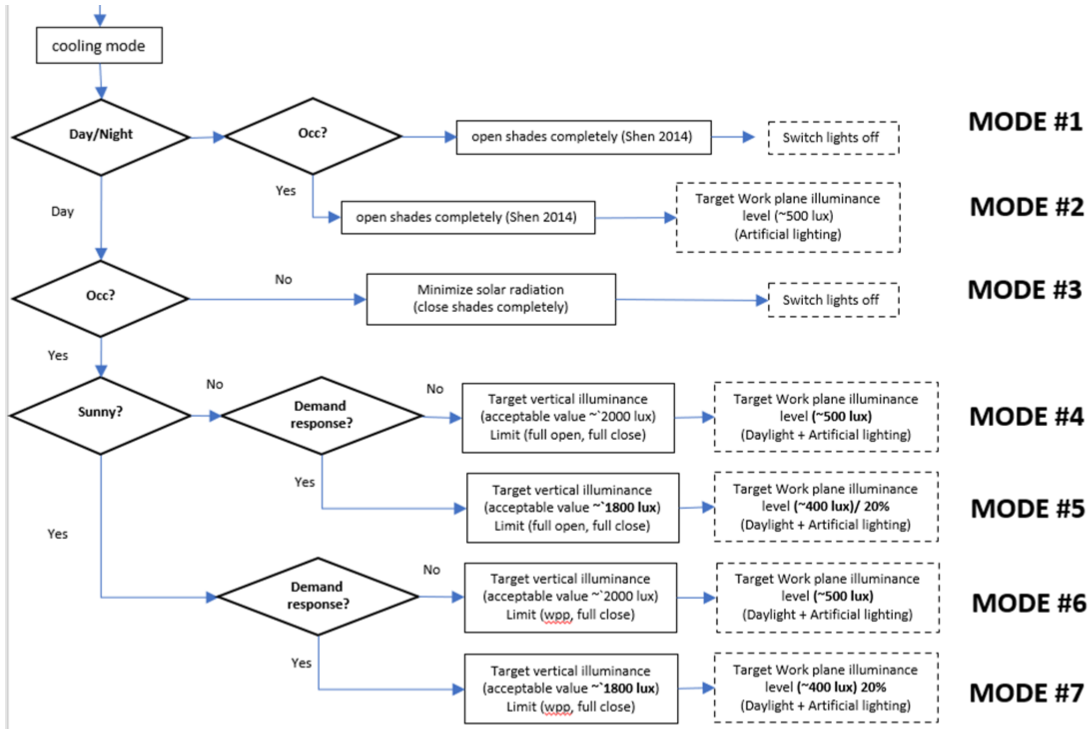

Figure A.1 Control modes for cooling

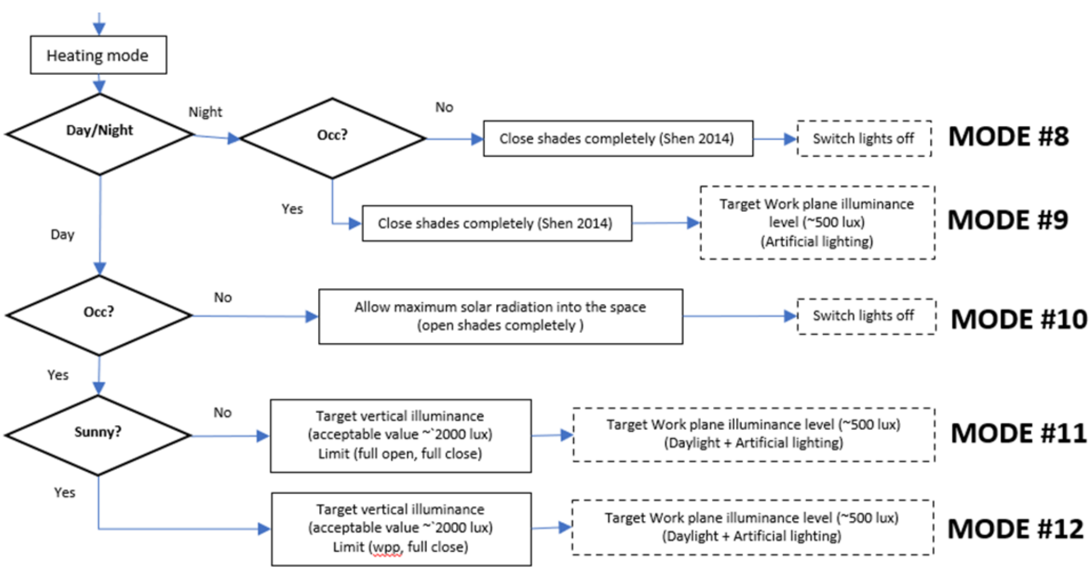

Figure A.2 Control modes for heating

The lighting levels were updated in EnergyPlus by updating the LPD values to reflect lighting power change for all time steps (for making adjustments for task tuning, and the switching to LED fixtures), while the lighting schedule was used to update lighting power for specific time steps (in case of daylighting and occupancy-based dimming). Task tuning refers to the capability to set the maximum light output to a less-than maximum state at the time of installation or commissioning. A study summarized the average task tuning factor for various building types using a sample of 194 buildings (Wen et al. 2020). The LPD was reduced by a factor of 0.64 to account for the use of all LED fixtures and was further reduced by a factor of 0.54 to account for task tuning (Wen et al. 2020). To account for unoccupied times, the lighting schedule was updated to zero. For daylighting, the lighting was dimmed such that the target values at the work plane sensor were 300 lux in *Energy Savings* mode, and 240 lux for *Demand Response* mode. The LPD values were assumed to reduce linearly with a reduction in the illuminance (lux) values.

RESULTS

Daylighting model

The daylighting model was used to generate annual illuminance values for both the vertical and the work plane sensor for various shade positions. The daylighting software was designed to operate in the roller shade with 11 shade positions (fully closed, 90% closed, 80% closed, … 10% closed, fully open). Figure 2 shows the resulting illuminance values for the vertical sensor for all 11 shade positions for the south facing zone for summer solstice (20th June) and winter solstice (21st December).

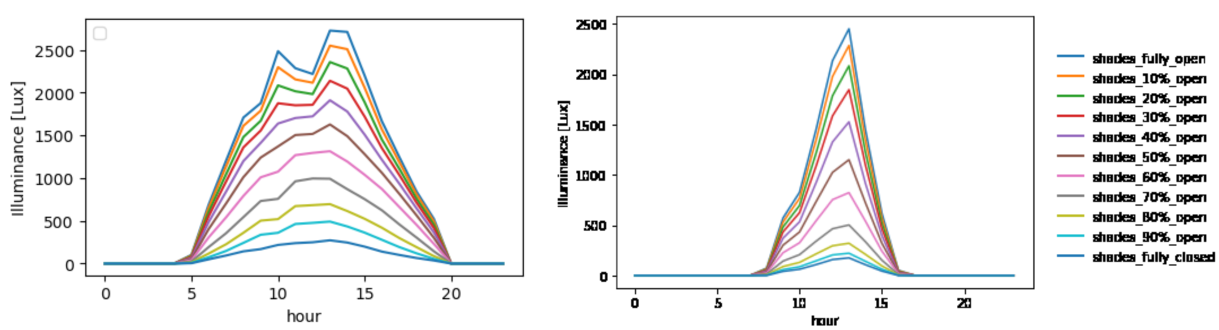

Figure 2. Illuminance values for the vertical sensor on the summer solstice (left) and winter solstice (right) for the small office building for the south facing zone.

Shade control and lighting control model

From the set of illuminance values generated in the first step, a suitable illuminance value is selected based on the control mode to reduce occupant visual discomfort and optimize solar heat gain. For example, in Mode 6 (see Table 2), a suitable shade position is selected to restrict the vertical illuminance to 2000 lux by closing the shades. However, in Mode 3 the shades are directed to be fully closed to minimize the solar heat gain in cooling mode when the space is unoccupied. Figure 3 shows the control modes and selected shades position based on these control modes for summer and winter solstice. For the summer solstice, the shades are closed partially closed on midday and completely closed in the evening. The shades are fully closed in the evening due to the control mode being Mode 3 which is when the zone is unoccupied during a cooling period. The shades are closed fully to minimize the incoming solar radiation in the space.

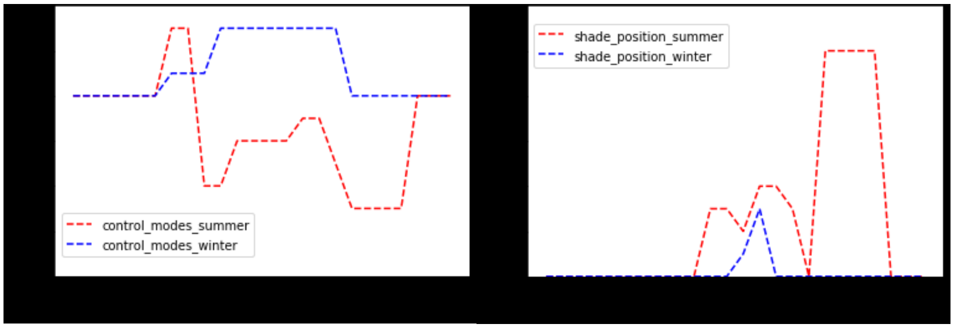

Figure 3. Control modes (left) and selected shade position (right) for the south facing zone on the summer and winter solstice

Energy model

After the shade position selection, the lighting levels are then adjusted as per Table 2. Figure 4 shows the lighting energy consumption for the *Baseline* model and the *Energy Savings* model. For the summer solstice (left), the lighting energy for *Energy Savings* mode is 0 kWh, as the available daylight is above 300 lux whenever the zone is occupied. However, for winter solstice (right), for some hours in the morning (7:00 to 10:00 am) and evening (3:00 to 5:00 pm), the available daylight is lower than 300 lux and thus some lighting energy consumption is observed for these hours.

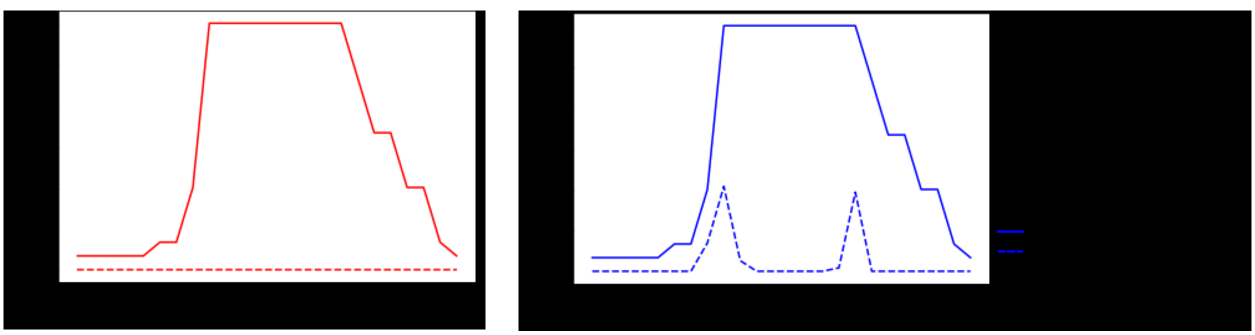

Figure 4. Lighting energy for the south facing zone on summer (left) and winter (right) solstice

Figure 5 shows the cooling load for the *Baseline* model and the *Energy Saving* model for the summer solstice along with the heating energy consumption for the *Baseline* model and the *Energy Saving* model for the winter solstice. Cooling and heating load for winter and summer solstice respectively, are zero for both the *Baseline* and *Energy Savings* model, thus they are not shown in Figure 5.

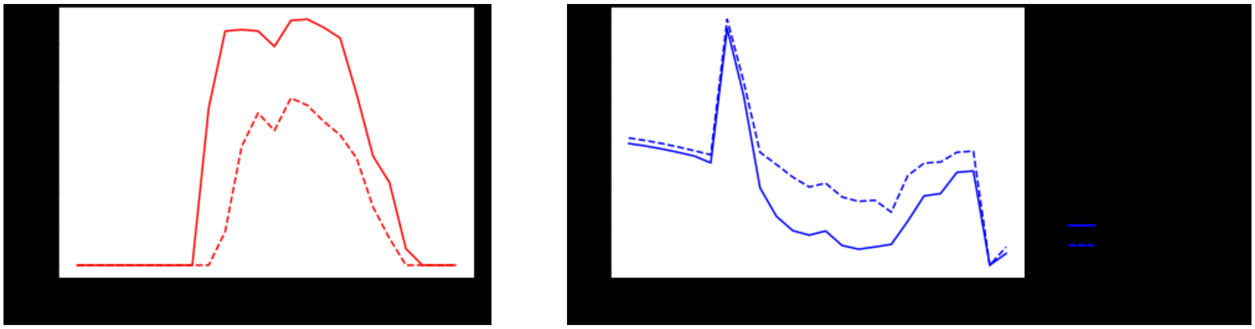

Figure 5. Cooling energy on summer solstice (left) and heating energy on winter solstice for south facing zones

The cooling load for the *Energy Saving* model decreases while the heating load increases. The decrease in cooling is both due to the decrease in the LDP level and the closing of shades. The increase in heating load is due to closing of shades to prevent occupant glare as compared to the baseline model. Table 3 provides the annual load for cooling, heating, and lighting energy consumption and the percent change from the baseline model.

Table 3. Annual heating and cooling load and lighting energy consumption for south facing zone (all values in kWh) in *Energy Savings* mode

	Baseline model (kWh)	**Energy savings model (kWh)**	**% Energy savings**
Cooling load	2,590	1,861	28%
Heating load	6,276	7,652	-21%
Lighting load	4,345	1,501	65%

Demand response model results

The *Demand Response* model results represent the cooling demand saving potential as compared to the *Baseline* model for all timesteps between the 2 pm and 5 pm and the control mode is in Mode 5 or Mode 7, those are the only modes when demand response is considered.

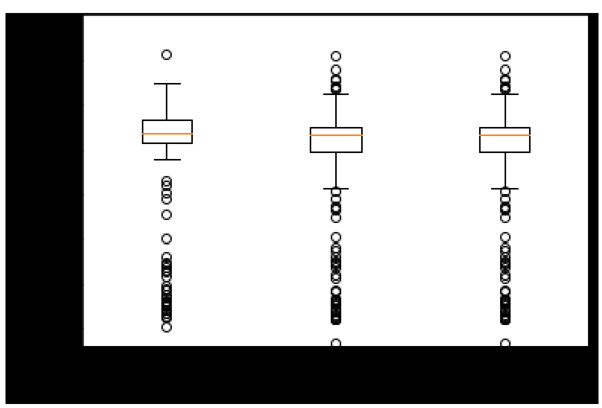

Figure 6. Demand reduction in cooling load for the south facing zone of a small office building during a demand response event (2 pm to 5 pm)

Figure 6 shows the cooling demand reduction in kW for the *Demand Response* model The *Demand Response* model demonstrated a mean reduction of 1.00 - 1.25 kW for the south facing zone. Currently the preliminary model uses a fix demand response period of 2 to 5 pm, however the specific location, varying by climate zones or grid load dynamics will be considered in future.

CONCLUSIONS

A preliminary model was developed for a small office building to compare a *Baseline* reference case with an updated model that includes dynamic shading and automated lighting. RADIANCE was used to create a daylighting model to determine illuminance values at two sensor locations, which was later used for selection of shading height and dimming the lighting levels with various control modes. The 12 chosen control modes were developed based on different input variables including HVAC operation, time of day, occupancy, solar irradiance, and others. The energy consumption for cooling, heating and lighting compared to the *Baseline* model were reported for both *Energy Savings* and *Demand Response* control modes. The results suggest an estimated cooling load reduction of 28% and heating load increase of 21% for the south facing zone for a small office building. Similarly, the lighting energy consumption was reduced by 65% as compared to the *Baseline* model in *Energy Savings* mode. We note that the baseline model used fluorescent lights (baseline LPD = 10.8 W/m^2) while the *Energy Savings* model used all LED fixtures with task tuning, daylight, and occupancy sensing, thus the substantial decrease in consumption. The *Demand Response* model demonstrated a mean reduction of 1.00 - 1.25 kW in cooling demand for south facing zone across the year-long simulation period during 2 pm to 5 pm.

A similar modeling process will be completed for all the zones in a small and medium sized office building. In addition, while in this research the HVAC operation, time of day, occupancy and solar irradiance were used for selection of control mode, more variables such as solar penetration and solar heat gain in space can be investigated for a more nuanced control strategy. Further, a sensitivity analysis for various variables such as window-to-wall ratio, sensor positions, shade material selection, and illuminance threshold, among others, may be conducted for different zones to optimize the energy and demand savings potential.

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