Comparison of Energy and Visual Comfort Performance of Independent and Integrated Lighting and Daylight Controls Strategies

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ABSTRACT

Automated electric lighting systems and motorized shading systems have been widely used in buildings to minimize lighting and HVAC energy consumption and improve visual comfort. Existing lighting and shading systems typically operate independently, i.e. information is not shared. Although integration of control systems has been proposed to maximize energy efficiency and user comfort these benefits have not been quantified. To address this we performed an in-depth study of one manual, four independent and two integrated control strategies:

1. Manual control of lights and no blinds
2. Independent open-loop blind, closed-loop dimming control
3. Independent open-loop blind, closed-loop dimming control, occupancy and HVAC mode shared with blind system
4. Independent closed-loop blind, closed-loop dimming control
5. Independent closed-loop blind, closed-loop dimming, occupancy and HVAC mode shared with blind system
6. Fully integrated lighting and daylighting control with blind tilt angle control without blind height control
7. Fully integrated lighting and daylighting control with blind tilt angle and height control

Simulation results for a reference office building are presented for three climate zones (Baltimore, London, Abu-Dhabi), two types of blinds (interior, exterior) and two window-to-wall ratios (66%, 100%). A dynamic occupancy model was developed from actual office occupancy data and used in the simulations. The results show the breakdown of lighting, heating, and cooling energy consumption. Visual comfort is quantified in terms of ability to maintain illuminance within the desired range and daylight glare index below the acceptable norm. Overall, in most cases, strategy six outperforms all other strategies in energy and visual comfort performance.

Introduction

According to the Buildings Energy Data Book, lighting consumed 20.2% of the commercial building energy in U.S. in 2010 (PNNL 2011). It is therefore imperative to develop strategies that minimize the lighting energy usage intensity to realize low-energy sustainable buildings. Advanced lighting controls offer one of the most cost-effective means to reduce the energy, carbon footprint, and operating costs of existing buildings, and to improve occupant satisfaction by providing personal control over light conditions.

Electric lighting control and daylight (blinds or shades) control are both essential for regulating interior lighting conditions. The use of on/off or dimmable lighting systems integrated with automated blinds can block direct sunlight, provide the design workplane illuminance, and save energy (Galasiu et al. 2004). These integrated systems can result in lighting energy savings of 30-77% (Ihm et al. 2009; Tzempelikos & Athienitis 2007).

Existing lighting and blind/shade control systems typically operate independently to regulate interior illuminance while external daylight conditions vary (Li & Lam 2001; Reinhart 2004). These types of systems use the independent control approach where there is no sharing of information between different control systems. The independent approach is found to be sub-optimal in energy efficiency and sometimes causes inconvenience to users (Koo et al. 2010).

To address these limitations of the independent approaches, the integrated approach, that is, integration of electric lighting control and blind control systems, has been proposed (Mukherjee et al. 2010; Patel et al. 2011). In the integrated approach, the electric lighting and the blinds are controlled in an integrated manner by sharing the occupancy and interior illuminance information between the two subsystems to minimize energy consumption while maintaining the required light level on the work surface. However, some of these systems are not integrated with HVAC systems though the daylighting and lighting levels may significantly affect cooling and heating loads. Moreover, the benefits of the integrated control approaches have not been quantified in the literature leaving the room for subjective interpretations. Therefore, in this research, seven control strategies were compared to quantify the benefit of the fully integrated control. The main comparison metrics are the year round energy and visual comfort performance. Specifically, the breakdown of lighting, heating, cooling and total energy consumption is quantified. Visual comfort is gauged in terms of ability to maintain the illuminance in the desired range and daylight glare index below the acceptable norm.

Lighting and Daylighting Control Strategies

Building control strategies can be broadly divided into open-loop and closed-loop controls (Mukherjee et al. 2010). Open-loop controls are those that adjust the output based on external input only. Closed-loop strategies employ feedback along with external input to regulate the output. In this research, we have explored both open-loop and closed-loop controls of window blinds, closed-loop control of electric lights, and integrated controls of these building subsystems.

Manual Control Strategy

Strategy 1: Manual controls and no blinds. No blinds are installed in the window. Lighting is manually switched as modeled via dynamic occupancy model. Lights are turned on when the occupant first arrives and turned off when the occupant leaves after 6:00pm. There is no daylight dimming of lights.

Independent Control Strategies

Strategy 2: Independent open-loop blind and closed-loop dimming. Blinds are always fully deployed. The blind slat angle during the day is set to the cut-off angle to block beam solar (open-loop). The cut-off angle is calculated based-on latitude, longitude, orientation of window, date, local time and slat geometry using well-known theoretical models (Zhang & Birru 2012). The model accounts for a variety of space geometry and configuration parameters to block direct sun. At night, the blind slats are completely closed. Lighting is controlled by occupancy-based switching with a ten minute timeout setting. Lighting is also controlled by daylight-based dimming to maintain a target illuminance of 500 lux at the reference location located in the workplane with a distance of 0.76 m from floor and a distance of 2.82 m from window.

Strategy 3: Independent open-loop blind, closed-loop dimming, occupancy sharing and HVAC link. When space is occupied, the blinds operate in a comfort mode to ensure the visual comfort of the occupant. When space is unoccupied, the blinds operate in an energy saving mode (see Table 1). The blind slat angle when occupied during the day is set to the cut-off angle to block beam solar (open-loop). When unoccupied during the day and the HVAC system is operating in cooling mode the blind slats are completely closed to block solar heat gain, and if the HVAC system is operating in heating mode, the blind slats are opened (slats are perpendicular to the window) to allow solar heat gain. The blind slats are controlled in opposite at night. Lighting is controlled by occupancy-based switching with a ten minute timeout setting. Lighting is also controlled by daylight-based dimming to maintain a target illuminance of 500 lux at the reference location (closed-loop).

Table 1. Blind Control Modes and Slat State Settings

Time	**Occupied**	**Blind control mode**	**Blind slat state**	
			HVAC heating	**HVAC cooling**
Daytime	Yes	Comfort mode	Cut off angle (open-loop)	
	No	Energy saving mode	Open	Closed
Night	Yes/No	Energy saving mode	Closed	Open

Strategy 4: Independent closed-loop blind and closed-loop dimming. Blinds are always fully deployed. During the day when glare is not detected, the slat angle is controlled to regulate the daylight admission to maintain the target illuminance at the reference location (closed-loop). When glare is detected, the maximum permissible slat angle opening is set to the cut-off angle. Daylight admission is regulated to achieve the target illuminance at the reference location (closed-loop) while ensuring that the slat angle stays within the permissible range (i.e. between fully closed and the cut-off angle). At night, the blind slats are completely closed. Lighting is controlled by occupancy-based switching with a ten minute timeout setting. Lighting is also controlled by daylight-based dimming to maintain a target illuminance of 500 lux at the reference location (closed-loop). Note that the blind and lighting controls operate independently.

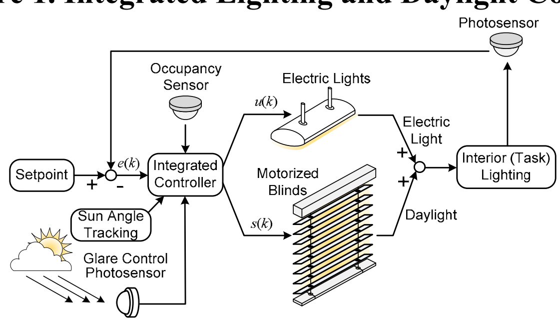
Strategy 5: Independent closed-loop blind, closed-loop dimming, occupancy sharing and HVAC link. This blind control strategy is similar to Strategy 3 (see Table 1). The major difference is that during comfort mode, the blind slats are controlled in closed-loop. During the day when glare is not detected and space is occupied, the slat angle is controlled to regulate the daylight admission to maintain the target illuminance at the reference location (closed-loop). When glare is detected and space is occupied, the maximum permissible slat angle opening is set to the cut-off angle. Daylight admission is regulated to achieve the target illuminance at the reference location (closed-loop) while ensuring that the slat angle stays within the permissible range (i.e. between fully closed and the cut-off angle). The lighting control is the same as Strategy 3, i.e. controlled by occupancy-based switching with a ten minute timeout setting and daylight-based dimming to maintain a target illuminance of 500 lux at the reference location (closed-loop). Note that there is no control integration, i.e. the blind and lighting controls operate independently, although occupancy and HVAC system status is shared.

Integrated Control Strategies

Strategy 6: Fully integrated lighting and daylighting control with blind tilt angle control without blind height control. Blinds are always fully deployed. The control strategies of blind and lighting systems are fully integrated and operate as a one system with full knowledge of control system parameters. The main difference between Strategy 5 and Strategy 6 is that in Strategy 5 when the space is occupied during daytime, the blind control system and lighting control system independently regulate the light level to achieve target illuminance at the reference location. On the other hand, in Strategy 6 the integrated system operates as one system to maintain the target illuminance.

In energy saving mode, the control is the same as Strategy 5. In comfort mode (i.e., when the space is occupied during daytime), the control strategy is illustrated in Fig. 1. When the space is occupied during daytime and there is insufficient light to reach the target illuminance and blind slats are partially open, then the integrated controller attempts to open the blind slats incrementally to admit more daylight while ensuring that slat angle stays within the permissible range decided by the glare control strategy. If the target illuminance cannot be reached even after the blinds slats are open to the maximum extent possible, the electric lights are incrementally brightened to compensate for insufficient daylight (note that in practice to avoid insufficient light during the adjustment period when blinds start to open, the lights may also be adjusted in parallel). Similarly, when the interior illuminance is above the target, the electric lights are slowly dimmed, and if the target illuminance is not reached even after the lights are turned off, then blind slats are closed incrementally to reduce daylight admission until the illuminance meets the target (Patel et al. 2011).

Figure 1. Integrated Lighting and Daylight Control



Strategy 7: Fully integrated lighting and daylighting control with blind tilt angle and height control. The blind slat control and lighting controls are identical to Strategy 6. The blind height is controlled using the open-loop strategy that limits the direct sunlight penetration to a pre-configured depth.

Simulation Methodology

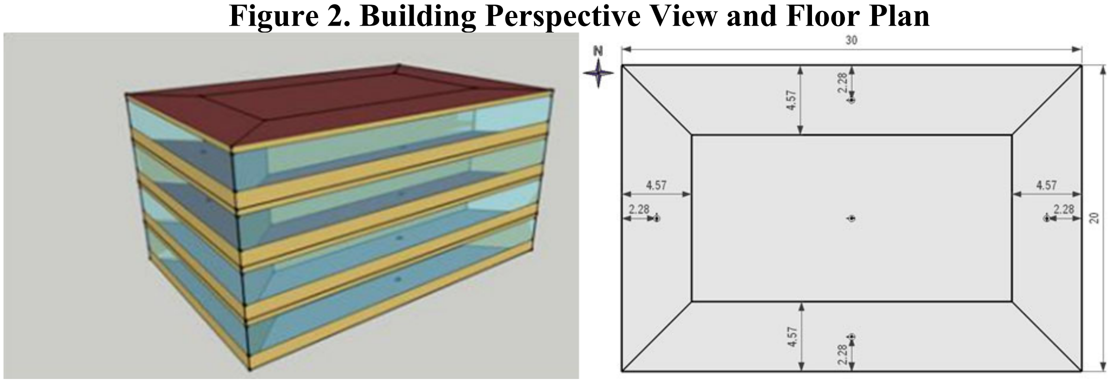
Simulations were run using a simulation platform that co-simulates EnergyPlus and Matlab using a middleware interface Building Controls Virtual Test Bed (BCVTB). The BCVTB, a platform developed by Lawrence Berkeley National Laboratory, allows users to couple different simulation programs in order to conduct detailed building energy simulations. It allows modeling of various control strategies and studying their year round performance in a variety of climate zones. EnergyPlus, building energy simulation program developed by the U.S. Department of Energy, can model the building and all aspects of building energy performance. Matlab is a numerical computing program developed by MathWorks. It implements the detailed lighting and blind control algorithms and dynamic statistical occupancy in this research. This results in accurate simulation of controls performance that is not possible to achieve in existing standalone tools.

Building Simulation Parameters

The 3D modeling software SketchUp and its OpenStudio plugin were used to create the building models that were simulated in EnergyPlus. Some dynamic parameters were setup to investigate the influence of building parameters on the performance of the control strategies. The dynamic building parameters include (1) three geographical locations: Abu Dhabi, London and Baltimore; (2) two types of blinds: interior horizontal blinds and exterior horizontal blinds; and (3) two window-to-wall ratios: 66% and 100%. For cities outside the U.S., the climate characteristics were mapped to similar climate zones within the U.S. in order to determine the appropriate building envelope characteristics. Other key building simulation parameters were:

1) Building geometry thermal zones: The building has four floors and a rectangular shape with aspect ratio of 1.5 (see Figure 2); it has flat roof and ground on slab construction; each floor is 30m x 20m and consists of 38% core and 62% four perimeter zones; on each floor, there are four perimeter zones, each 4.57m deep, with windows facing each direction, which receive daylight; and the core zone does not receive any daylight.

Figure 2. Building Perspective View and Floor Plan



2) Envelope: The building envelope characteristics are consistent with ASHRAE 90.1-2004 standards (except for glazing); exterior walls are steel-framed consisting of three layers, an outer sheath layer (R = 0.36 $m^2 \cdot K/W$), the primary wall insulation (R = 0. 83 $m^2 \cdot K/W$), and an inner ½ inch gypsum layer (R = 0.08m $^2 \cdot K/W$); single pane 6mm clear glass (visible transmittance = 0.881, SHGC = 0.818, U-factor = 5.785 W/m^2K) was used; blind solar and visible reflectance was set to 0.5.
3) Lighting: Lighting power density was set to 11.52 W/m^2; LED lighting system was used.
4) Plug loads: The electrical plug loads (8.07 W/m^2) are controlled based on recommended ASHRAE standard schedules and are thus the same for all strategies.
5) Occupancy: the density was set to 3.91 people/100m^2. Occupancy is primarily controlled by a dynamic statistical occupancy model derived from actual data from a typical office

building. In order to achieve a typical target occupancy hours per day on weekdays, the dynamic occupancy model is used before 6:00pm, and scheduled occupancy hours are used at night.

6) HVAC settings: For simplicity (i.e. to avoid convergence issues), the HVAC system was chosen to be packaged single zone AC units consisting of electricity driven cooling coils and natural gas fuelled heating coils (COP =3.0); Cooling set point was set to 24°C with setback to 30°C; Fan efficiency was set to 60%; Heating set point was set to 21°C with setback to 15.6°C and heating efficiency was set to 80%.

Control Simulation Parameters

For all implementations of daylight dimming, electric lights are controlled so that the total illuminance at the reference point is 500 lux. The reference points are located along the centerlines of the perimeter zones at a distance of 2.28m from the window (50% deep into the zone) and at a height of 0.762m (30" typical work plane height). All illuminance values for control and metrics are referenced at this position. For discomfort glare index (DGI) calculations, the view angle is 90 degrees from the window at the reference point.

In control strategies that have an explicit glare control feature, the glare control is activated when the exterior illuminance on the window reaches (or exceeds) a threshold of 60,000 lux. This value was determined through a simulation study to be a reasonable threshold for glare control. Control modes that differentiate between night and day utilize the solar profile angle to determine daytime and night time. When all the solar profile angles are zero for all the building window surfaces, there is no daylight (direct or diffuse) incident on the building.

For variable blind height controls, each window in the EnergyPlus model is segmented into ten sub-windows to implement variable blind height in ten percent increments. This is necessary to model a window section without blind and a window section with blind. For open-loop blind height control (Strategy 7) based on daylight penetration depth, the daylight penetration depth is set to 0.57m.

For closed-loop slat angle controls, the slat angle is changed in five degree increments. The minimum time step in the simulation is one minute. Also, in order to avoid oscillations, if a slat angle has been changed in one time step it cannot be changed in the subsequent time step. This is an artifact of the information exchange between EnergyPlus and Matlab and the BCVTB. Thus, the maximum speed of blind angle change is limited to five degrees every two minutes.

Results

Lighting Energy Consumption

The lighting energy consumption in perimeter zones for all seven strategies is shown in Table 2. The performance ranking of the seven control strategies with respect to lighting energy consumption is 7 > 6 > 3 > 2 > 4 > 5 > 1. The core areas of the building do not receive daylight and are treated as open areas so occupancy related savings are limited. The perimeter zones receive daylight and are treated as private offices, hence the lighting energy savings are mainly from perimeter areas. For control Strategies 2 through 7, the occupancy-related lighting savings are the same and the discussion focuses mainly on the perimeter zones and interaction of blind controls and electric lighting controls.

Table 2. Lighting Energy Consumption in Perimeter Zones (10^3 kWh)

Building Models	Control Strategies						
	1	2	3	4	5	6	7
A,66%,ext.	46.7	6.4	5.85 (8.8%↓)	9.4	27.0(186.5%↑)	5.3	4.1 (21.7%↓)
A,66%,int.	46.7	6.3	5.78 (8.5%↓)	9.6	26.6(177.1%↑)	5.2	4.1 (21.4%↓)
A,100%,ext.	46.7	5.9	5.4 (9.4%↓)	9.4	25.9(175.6%↑)	4.8	3.9 (18.0%↓)
A,100%,int.	46.7	5.8	5.3 (9.0%↓)	9.6	25.4(164.8%↑)	4.8	3.9 (17.7%↓)
L,66%,ext.	46.7	13.0	12.4 (4.7%↓)	14.8	18.0 (21.7%↑)	11.8	7.4 (37.2%↓)
L,66%,int.	46.7	12.8	12.2(4.4%↓)	14.8	20.2 (37.0%↑)	11.7	7.4 (36.7%↓)
L,100%,ext.	46.7	11.3	10.7 (5.8%↓)	13.7	16.6 (21.5%↑)	10.1	6.9 (32.3%↓)
L,100%,int.	46.7	11.1	10.5 (5.4%↓)	13.7	19.0 (38.7%↑)	10.0	6.8 (31.8%↓)
B,66%,ext.	46.7	8.5	7.9 (7.9%↓)	11.2	19.8 (76.2%↑)	7.3	4.8 (35.0%↓)
B,66%,int.	46.7	8.4	7.7 (7.5%↓)	11.3	20.9 (85.9%↑)	7.2	4.7 (34.4%↓)
B,100%,ext.	46.7	7.3	6.63 (9.5%↓)	10.7	18.8 (76.9%↑)	6.1	4.4 (27.5%↓)
B,100%,int.	46.7	7.2	6.65 (8.9%↓)	10.7	20.0 (86.0%↑)	6.1	4.4 (26.9%↓)

Notes: the first column format is "location, WWR, blinds type". "A" = Abu Dhabi; "L" = London; "B" = Baltimore. This legend format applies to all the subsequent tables.

Strategy 1. Strategy 1 has the highest lighting energy consumption because the lights are turned on when the occupant arrives and stay on until after 6pm when the occupant leaves.

Strategies 2 and 3. Strategies 2 (independent open-loop control without occupancy sharing) and 3 (independent open-loop control with occupancy sharing) result in more energy consumption than Strategies 6 and 7 (integrated controls). Strategy 3 results in slightly less lighting energy consumption than Strategy 2 due to the occupancy sharing. Occupancy sharing results in lighting energy savings ranging from 8.5% to 9.4% in Abu Dhabi, 4.4% to 5.8% in London, and 7.5% to 9.5% in Baltimore for the various options of window-to-wall ratio and interior and exterior blinds (see Table 2).

Strategies 4 and 5. Strategy 4 (independent closed-loop control without occupancy sharing) and Strategy 5 (independent closed-loop control with occupancy sharing) consume more lighting energy than Strategies 6 and 7 (integrated controls) and Strategies 2 and 3 (open-loop controls). Strategy 5 has more energy consumption (i.e., 164.8% to 186.5% in Abu Dhabi, 21.5% to 38.7% in London, and 76.2% to 86.0% in Baltimore) than Strategy 4 for the various options of window-to-wall ratio and interior and exterior blinds (see Table 2).

In general, the independent closed-loop control strategies perform poorly because of slower response time of blind control system compared to lighting control system. Consider a scenario where the blind slats are partially open and daylight is sufficient to meet the target set point hence, the electric lights are off. Now suddenly the clouds appear in the sky so the internal illuminance drops below the target set point. The closed-loop blind control system will react to this change by opening the blinds in five degree increments. At the same time the closed-loop lighting control system increases the electric lights to reach the set point. Since the response time of electric lights is faster than blinds, the set point will be met before the blinds have opened to make full utilization of available daylight. Thus a steady state is reached where blinds are partially open and electric lights are on which is not optimal. In the case of integrated controls, the blinds will continue to open as long as the electric lights are on even if the set point is reached. This will enable the blinds to open further and if there is sufficient daylight then electric lights will be gradually turned off.

Adding occupancy sharing and HVAC link (Strategy 5) results in significantly worse lighting performance than Strategy 4. In Strategy 5, when the HVAC is in cooling mode and space is unoccupied, the blinds are kept closed to save cooling energy. If the blinds are closed when the occupant enters the space, the closed-loop lighting control method will turn the lights fully on to meet the set point. Given that the set point has been reached, the closed-loop blind control system concludes that there is no need to open the blinds any further thereby not harvesting the daylight to its fullest potential. Thus in climates and seasons when cooling mode is dominant, the blinds will tend to keep closed and thus the lighting energy consumption will be higher compared to other strategies.

Strategies 6 and 7. Strategy 7 (with height control) has the lowest lighting energy consumption. Strategy 6 (without height control) has lower lighting energy consumption than Strategies 1-5. The height control strategy regulates the blind height such that direct daylight does not penetrate the space beyond the allowable penetration depth. This means the blinds are fully raised up for a significant portion of daytime allowing more daylight to enter the space thereby lowering the lighting energy consumption. For the various options of window-to-wall ratio and interior and exterior blinds, compared to Strategy 6, the lighting energy savings in Strategy 7 ranges from 17.7% to 21.7% in Abu Dhabi, 31.8% to 37.2% in London, and 26.9% to 35.0% in Baltimore (see Table 2).

Heating Loads

Heating loads in perimeter zones are shown in Table 3. Heating loads vary by climate and blind type. In general, Strategies 1, 3 and 7 have lower heating loads compared to other strategies. Strategy 1 has low heating loads because the absence of blinds allows maximum solar heat gain during the day. Strategy 3 benefits from occupancy link which allows it to open the blinds during daytime when space is unoccupied and HVAC is in heating mode thereby harvesting the solar heat gain. Strategy 7 (integrated control with height control) has low heating loads because blinds are raised for a significant portion of the daytime. Adding occupancy sharing and HVAC link to independent open-loop and closed-loop controls reduces heating energy in the mixed climates (e.g., Baltimore or Landon) with exterior blinds by 7.1% – 12.9%. Effects are less pronounced with interior blinds (see Table 3).

Table 3. Heating Loads in Perimeter Zones (10^3 kWh)

Building Models	Control Strategies						
	1	2	3	4	5	6	7
A,66%,ext.	3.2	4.3	4.4 (1.2%↑)	5.0	5.0 (0.6%↑)	4.7	4.1 (12.8%↓)
A,66%,int.	3.2	4.2	5.5 (32.3%↑)	4.7	5.6 (20.3%↑)	5.8	4.3 (25.8%↓)
A,100%,ext.	5.1	6.2	6.4 (3.4%↑)	7.8	7.8 (0.8%↓)	7.2	5.7 (21.8%↓)
A,100%,int.	5.1	6.2	8.3 (32.6%↑)	7.1	8.5 (19.6%↑)	8.7	5.7 (34.3%↓)
L,66%,ext.	153.9	147.7	137.2 (7.1%↓)	156.7	142.8 (8.9%↓)	140.6	140.5 (0.1%↓)
L,66%,int.	153.9	152.9	154.9 (1.3%↑)	156.6	155.9 (0.4%↓)	156.8	135.0 (13.9%↓)
L,100%,ext.	218.7	200.0	185.4 (7.3%↓)	217.1	195.3 (10.0%↓)	192.4	186.7 (3.0%↓)
L,100%,int.	218.7	212.0	214.8 (1.3%↑)	218.1	216.9 (0.6%↓)	218.1	184.6 (15.3%↓)
B,66%,ext.	105.0	129.0	115.9 (10.2%↓)	137.0	121.1 (11.6%↓)	119.1	114.7 (3.7%↓)
B,66%,int.	105.0	112.6	111.4 (1.0%↓)	116.0	112.9 (2.7%↓)	113.3	97.1 (14.2%↓)
B,100%,ext.	148.3	171.2	153.1 (10.6%↓)	186.2	162.1 (12.9%↓)	159.3	147.5 (7.4%↓)
B,100%,int.	148.3	153.8	152.3 (1.0%↓)	159.2	154.7 (2.9%↓)	155.4	131.1 (15.7%↓)

Cooling Loads

Cooling loads in perimeter zones are shown in Table 4. The performance ranking is 5 > (6, 4) > 3 > 2 > 7 > 1. Strategy 5 generally consumes less cooling energy than the other strategies. The blinds remain partially closed in occupied state because the lighting set point is quickly reached due to a relatively faster response by electric lights than blinds which adapt slowly to changes in internal illuminance environment. Partially closed blinds reduce daylight admission into the space which increases the need for electric lights but reduces the need for cooling. Therefore, in some scenarios the cooling energy consumption is the lowest in Strategy 5. However, in all strategies the total energy consumption is not the lowest because cooling energy reduction is more than offset by higher lighting energy consumption. Strategy 5 reduces cooling energy by 2.8% – 9.8% compared to Strategy 4 (except in London) by adding occupancy sharing (See Table 4).

Strategy 6 performs better than Strategies 1, 2, 3 and 7 mainly because of reduced solar heat gain due to optimized blind control. Note that Strategy 6 opens the blinds until the set point is reached and not any further. This strategy minimizes the lighting energy consumption by harvesting the natural light to the maximum extent possible while avoiding the excessive solar heat gain.

Strategy 3 consumes less cooling energy (8.1% – 22.3%) than Strategy 2. This is because using HVAC link and occupancy information, the behavior of the blinds during unoccupied times is optimized to save cooling energy, i.e. blinds are closed during daytime when space is unoccupied to reduce solar heat gain.

Strategy 7 has the second highest cooling loads after Strategy 1 because the blinds are fully raised for a significant portion of daytime and more solar heat is admitted compared to all other blind control strategies.

Strategy 1 features manually controlled non-dimmable lights and no blinds. Among all the strategies, it admits the maximum solar heat gain and has the highest thermal load of lighting.

Table 4. Cooling Loads in Perimeter Zones (10^3 kWh)

Building Models	Control Strategies						
	1	2	3	4	5	6	7
A,66%,ext.	661.2	292.0	260.2 (10.9%↓)	235.5	219.3 (6.8%↓)	230.9	304.1(31.7%↑)
A,66%,int.	661.2	502.7	459.1 (8.7%↓)	462.9	437.4 (5.5%↓)	436.5	478.9 (9.7%↑)
A,100%,ext.	874.8	365.5	319.9 (12.5%↓)	273.1	254.2 (6.9%↓)	269.9	400.6 (48.4%↑)
A,100%,int.	874.8	670.7	610.2 (9.0%↓)	608.5	571.7 (6.1%↓)	574.4	651.1 (13.3%↑)
L,66%,ext.	127.4	26.9	21.5 (20.2%↓)	11.6	11.7 (0.7%↑)	13.4	29.2 (117.3%↑)
L,66%,int.	127.4	83.9	77.1 (8.1%↓)	68.9	69.3 (0.6%↑)	69.0	82.4 (19.4%↑)
L,100%,ext.	177.2	36.8	28.6 (22.3%↓)	12.1	12.7 (5.4%↑)	14.7	45.2 (208.7%↑)
L,100%,int.	177.2	120.5	110.7 (8.1%↓)	96.1	96.5 (9.8%↓)	96.9	119.7 (23.5%↑)
B,66%,ext.	268.8	87.8	74.4 (15.2%↓)	61.0	55.0 (2.8%↓)	60.4	94.9 (57.2%↑)
B,66%,int.	268.8	188.9	173.4 (8.2%↓)	168.0	163.3 (9.6%↓)	161.7	184.8 (14.3%↑)
B,100%,ext.	363.7	112.6	93.0 (17.4%↓)	68.1	61.6 (3.0%↓)	68.4	130.3 (90.6%↑)
B,100%,int.	363.7	259.7	238.4 (8.2%↓)	226.0	219.2 (8.8%↓)	218.9	256.7(17.2%↑)

Illuminance Levels

Table 5 shows the percentage of occupied time during day where the daylight illuminance levels are within the range of 300 lux to 1000 lux for each control strategy as evaluated in the second floor south-facing zone. The performance ranking is 6 > (4, 5) > 7 > 3 > 2 > 1. Strategy 6 performs the best, consistently across all climate zones, because daylight illuminance is properly controlled to the desired levels. Strategies 4 and 5 performance varies widely. Strategy 5 performs poorly with the worst performance in cooling-dominated climates. Strategy 7 results in poor performance compared with Strategy 6 due to the excessive daylight entering the space. Strategies 2 and 3 generally perform very poorly, indicating that open-loop slat angle controls based on cut-off angle are not sufficient to limit daylight illuminance to desired levels.

Table 5. Illuminance Levels in Second Floor South-facing Zone

Building Models	Control Strategies						
	1	2	3	4	5	6	7
A,66%,ext.	0.6%	18.2%	18.8%	81.6%	7.9%	83.6%	10.7%
A,66%,int.	0.6%	18.2%	18.8%	81.2%	6.4%	83.0%	10.5%
A,100%,ext.	0.5%	6.5%	6.9%	81.1%	7.8%	80.8%	7.5%
A,100%,int.	0.5%	6.4%	6.8%	80.0%	8.6%	80.1%	7.3%
L,66%,ext.	9.1%	26.9%	27.7%	61.6%	44.0%	69.5%	32.7%
L,66%,int.	9.1%	26.5%	27.3%	61.1%	34.1%	69.2%	32.4%
L,100%,ext.	8.0%	22.1%	22.8%	65.0%	47.3%	71.6%	33.3%
L,100%,int.	8.0%	21.9%	22.7%	63.7%	36.1%	71.1%	33.0%
B,66%,ext.	2.3%	27.6%	28.6%	72.1%	32.2%	79.7%	26.3%
B,66%,int.	2.3%	27.8%	28.8%	71.5%	25.0%	79.2%	25.7%
B,100%,ext.	1.9%	17.4%	18.2%	72.6%	32.5%	78.5%	23.0%
B,100%,int.	1.9%	17.1%	17.9%	71.7%	25.3%	77.8%	22.6%

Glare Levels

Table 6 shows the percentage of occupied time during day where the discomfort glare index (DGI) was below 22 in the second floor south-facing zone. A DGI of 22 is considered to be the maximum acceptable DGI for office work (Chaiwiwatworakul et al. 2009). The performance ranking is (4, 5) > 6 > (2, 3) > 7 > 1. Strategies 4 and 5 perform very well with respect to glare because of the coincidence that blind slats tend to stay partially closed. Strategy 6 performs well because daylight illuminance is properly controlled to the desired levels. Strategies 2 and 3 perform well with respect to limiting glare due to the cut-off angle. The performance of Strategies 2 and 3 is slightly worse than Strategy 6 because there can still be periods of high illuminance causing glare conditions. Adding blind height control (Strategy 7) results in poor performance due to the additional daylight entering the space.

Table 6. Glare Levels in Second Floor South-facing Zone

Building Models	Control Strategies						
	1	2	3	4	5	6	7
A,66%,ext.	34.6%	95.0%	95.0%	99.9%	100.0%	97.7%	53.1%
A,66%,int.	34.6%	95.0%	95.0%	100.0%	100.0%	97.8%	53.2%
A,100%,ext.	27.5%	95.1%	95.0%	100.0%	100.0%	98.2%	49.6%
A,100%,int.	27.5%	95.1%	95.0%	100.0%	100.0%	98.2%	49.8%
L,66%,ext.	41.9%	96.0%	95.7%	98.4%	97.8%	94.7%	66.6%
L,66%,int.	41.9%	96.0%	95.7%	98.6%	98.1%	95.0%	66.9%
L,100%,ext.	43.6%	95.8%	95.5%	99.0%	98.3%	95.5%	70.0%
L,100%,int.	43.6%	95.8%	95.5%	99.2%	98.5%	95.8%	70.3%
B,66%,ext.	29.7%	93.7%	93.2%	98.6%	98.1%	95.0%	57.9%
B,66%,int.	29.7%	93.6%	93.2%	98.6%	98.2%	95.1%	58.0%
B,100%,ext.	30.8%	93.3%	92.8%	98.6%	98.1%	95.3%	58.5%
B,100%,int.	30.8%	93.0%	92.6%	98.4%	98.0%	95.3%	58.7%

Conclusions

Testing independent and integrated control strategies using EnergyPlus, BCVTB and Matlab showed that Strategies 6 and 7 (integrated controls without/with blind height control) perform better than Strategies 2 – 5 (independent controls) overall. For lighting energy performance, the performance ranking is 7 > 6 > 3 > 2 > 4 > 5 > 1. Strategies 6 and 7 have the best lighting energy performance. Strategy 6 is better than Strategy 3 (independent open-loop controls with occupancy sharing and HVAC link) (4.4% – 10.6%) and Strategy 5 (independent closed-loop controls with occupancy sharing) (34.3% – 81.5%). In addition, adding occupancy sharing and HVAC link, Strategy 3 reduces lighting energy consumption compared to Strategy 2 while Strategy 5 increases lighting energy consumption compared to Strategy 4.

For heating energy performance, Strategy 7 generally has the best heating energy performance compared to other Strategies (-2.3% - 32.8%). Strategies 2 and 3 (independent open-loop controls) perform better than Strategies 4 and 5 (independent closed-loop controls).

For cooling energy performance, the performance ranking is 5 > (6, 4) > 3 > 2 > 7 > 1. Strategy 6 generally has good cooling energy performance (4.9% – 48.8% savings compared to

Strategy 3). Independent closed-loop controls (Strategies 4 and 5) perform better than open loop blind controls (Strategies 2 and 3). The specific case of independent closed-loop controls with occupancy sharing and HVAC link performs well due to blinds tending to stay closed (thus cooling savings are at the expense of increased lighting energy). For total lighting, heating and cooling energy performance, integrated controls achieve the lowest total energy in all cases. In most cases, Strategy 6 achieves the lowest total energy. In mixed humid climates and buildings with interior blinds, Strategy 7 achieves the lowest total energy.

For visual comfort performance, the performance rankings are 6 > (4, 5) > 7 > 3 > 2 > 1 for illuminance and (4, 5) > 6 > (2, 3) > 7 > 1 for glare. Strategy 6 generally has the best visual comfort performance. Strategies 4 and 5 (independent closed-loop controls) perform poorly with respect to daylight illuminance regulation (too little daylight), but perform artificially well with respect to daylight glare (because blind slats tend to stay closed). Strategies 2 and 3 (independent open-loop controls) perform poorly with respect to daylight illuminance regulation (too much daylight) and perform slightly worse than Strategy 6 with respect to glare.

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