MANUAL VS. OPTIMAL CONTROL OF EXTERIOR AND INTERIOR BLIND SYSTEMS

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ABSTRACT

Blind systems have been introduced to provide visual and thermal comfort, as well as to reduce energy use in buildings. A wide variety of such systems exist in terms of thermal and optical properties, location (exterior, interior), and physical configuration (size, distance between the blind slats). The current problem with blinds is that their operation is not based on the dynamics of the room (space), but on the static or manual control operated by occupants, although many studies have recognized that dynamic control can far outperform static control. One reason for the lack of dynamic control is that it is not easy to combine the room dynamics with any possible optimization algorithm. Hence, in this study, a whole building simulation tool, EnergyPlus, was integrated with MATLAB optimization toolbox to solve for optimal control of blind systems. This paper addresses the difference between static vs. dynamic control of interior and exterior blind systems in office buildings.

INTRODUCTION

Blind systems are used widely in buildings to provide visual and thermal comfort, as well as to reduce energy use. The performance of blind systems is influenced by the operation of the blind systems (change of slat angle). Studies on these systems in the past few decades can be classified as follows.

Step 1: static and not optimal

Cho et al. (1995) developed an analytical model of a window system with a venetian blind to calculate window surface temperature, which was validated by experimental data (Hayashi et al., 1989). The validated model was integrated with TRNSYS, and examined the impact on building energy use with different slat angles. The simulation runs were conducted in Seoul by varying the slat angle in 20° intervals to investigate variations in energy use. The experiment results are as follows: the optimal slat angle to minimize both heating and cooling loads is around 60° (slat toward the ground; horizontal position=0°) during the summer and -20° (slat toward the sky) during the winter.

Newsham (1994) examined the impact of manual control (lowered/retracted) of window blinds on annual energy consumption in Toronto, Canada. The following assumptions were made: (1) If solar radiation is greater than 233W/m^2, occupants would lower the blinds to avoid thermal discomfort. (2) Artificial lighting is turned off if work plane illuminance (horizontal) is above 500 Lux. (3) The room is occupied between 8:00 and 17:00. As a result, lighting and heating energy consumption was increased by 66% and 17%, respectively, and cooling energy consumption was decreased by 7%. Thus, the total energy consumption increased by 33%. This shows that that a blind system by itself, without a proper control, would not contribute to energy savings.

Step 2: dynamic but not optimal

Lee et al. (1998) studied the potential energy saving of automated venetian blinds operating in synchronization with daylighting controls in Oakland, California. To measure the electric lighting power consumption and the cooling energy produced by the window and lighting systems, the full-scale Oakland Federal Building demonstration facility was constructed. The facility consists of two adjacent identical rooms (4.57m (W)×3.71m (D)×2.68m (H)). For comparison, each room is equipped with a ‘base case’ system and ‘dynamic’ system. For the base case system, the venetian blind was set to one of three static positions throughout the day to simulate manual control: 0° (horizontal), 15° (partly closed), and 45° (nearly closed). For the dynamic system, a ‘prototype system’ was developed which activates the blind every 30s for blocking direct solar radiation and maintaining daylight illuminance of 540-700 Lux. The range of blind motion was restricted to 0°-68° to limit sky view and glare. Data were collected for 14 months from 1 Jun. 1996 to 31 Aug. 1997. Lee et al. (1998) concluded that an integrated system (or prototype system) could achieve energy savings of 7-15% and 19-52% for cooling and lighting energy, respectively, compared to a static 45° angle. However, because the automated blind system developed by Lee et al. only blocked the solar radiation, similar to that of Newsham (1994), it can be disadvantageous at places where the heating load is dominant. In other words, the optimization of blind systems can only be achieved if a criterion for selecting control variables is performance-based (sum of cooling, heating, and lighting energy use) rather than rule-based (threshold values of solar radiation and illuminance).

According to Bauer et al. (1996), a fuzzy logic-based control algorithm to minimize thermal and artificial lighting energy demand in a building was first developed by the Technical University of Vienna. Because of the algorithm limitation, which focused only on energy conservation, Bauer et al. (1996) proposed the modification of the TU-Wien controller for achieving energy efficiency, as well as thermal and visual comfort. The experiments were carried out in two south facing façade office rooms with a floor area of 15.6 m^2 and a window area of 3.77 m^2. Using the fuzzy logic-based smart blind controller, the experiments resulted in 11% lighting energy reduction, as well as 20%-50% heating/cooling energy savings.

Guillemin et al. (2001) applied a fuzzy logic and genetic algorithm (GA) to the adaptive controller for integrated operation of blinds, electric lighting, and HVAC systems. This technique was capable of adapting to user behaviour and the room characteristic. The adaptive controller was split into two parts depending on user presence: Upon detection of an occupant, visual comfort was optimized, otherwise energy saving was optimized. To achieve self-adaption, GA and ANN (artificial neural network) were employed. The experiments were carried out in two rooms with similar dimensions of 4.75m×3.6m×2.8m. Each room had integrated and conventional systems and a south facing window with textile blinds that were lowered or retracted by fuzzy logic rules, not including slat angle control. There is no blind or dimming control in the conventional system. Owing to the prediction ability of the controller, the integrated system reduced energy consumption by 25% over 94 days compared to the conventional system. The study (Guillemin et al., 2001) investigated the benefits of the fuzzy logic-based integrated system and achieved self-adaption using GA. However, what has been applied to the system is not a true optimal control in fact that the approach employed a rule-based control in determining the optimal control variables. The fundamental principle of the rule-based approach is “if this, do that” under certain circumstances. The disadvantage of this approach is that it does not reflect the transient behaviour of the system and adjacent rooms.

Kurian et al. (2008) explored building energy savings using fuzzy-based blind and artificial lighting control in Manglore, South India. The position of the blinds was closed, opened, or partially closed to reduce glare, solar heat gain, and provide uniformity of daylighting. ANFIS (adaptive neuro-fuzzy inference system) was applied to the daylight-artificial light integrated scheme for adaptation to changing environments and room characteristics. Artificial lighting was operated fully on, off, or in-between to satisfy the illuminance criteria (400 Lux). The fuzzy-based blind controller was operated by three criteria: (1) visual comfort mode (user present), (2) visual/thermal comfort mode (user present), and (3) energy optimization mode (user absent). The integrated fuzzy blind controller with daylighting controls could achieve 20-80% of annual energy savings compared to the base case of manual blind systems without daylighting control. Kurian et al. (2008) accomplished real-time control of integrated systems (artificial lighting and blinds) using ANFIS, but blind control was limited to position control (lowered/retracted) rather than that of slat angle, similar to the study by Guillemin et al. (2001).

Step 3: dynamic and optimal

Step 1 approached blind systems in a static manner rather than a dynamic manner. In other words, room condition and energy use were examined by fixing the blind slat angle. Step 2 developed an integrated scheme that is suited for a dynamic control system by applying a system identification technique to fuzzy logic and ANN. However, true optimal control was not employed since a definition and minimization of cost function does not exist. In this study, the blind control system is regarded as a dynamic system, and control variables to minimize cost function are derived hourly from an optimization routine. As shown in Figure 1, in previous studies the blind condition (slat angle and position of blind) was considered as a constant. However, in this study, we considered blind condition as a control variable; slat angle for optimizing building performance (energy, daylighting) was derived from iterative calculations in the optimization routine.

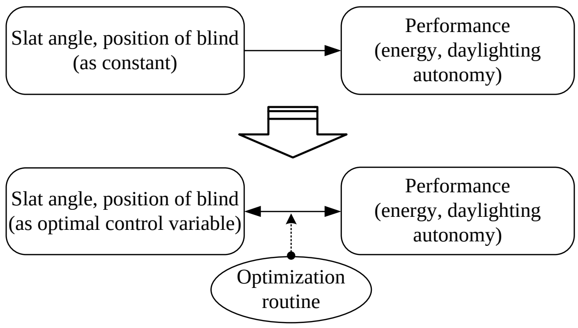


Figure 1 Optimal control of blind systems: From Steps 1, 2 to Step 3

SIMULATION MODEL

In order to examine the optimal control of blind systems, a simulation model was developed as shown in Figure 2. The model room has a rectangular space 2.8m (H), 3m (W) and 6m (D), and is assumed to be on the perimeter of a typical floor in a common office building. The window system, south facing, is 2.6m (W)×1.5m (H), and consists of a double glazing (6 mm clear+12 mm air cavity+6 mm low-e), which is commonly used in a typical office building. The blind system can be installed inside or outside of the room. The reflectivity of the slat was 0.5 (medium reflectivity) with a width, separation of slats, of 25 mm.

ASHRAE (2005) classifies the room characteristics in three types (lightweight, medium-weight, and heavyweight). In this study, the medium type of construction was chosen as it could be expected that the manual control may increase the sub-optimality that by default ignores the dynamic characteristics of the room. The room was assumed to have medium internal load densities of office space for lighting (16.15 W/m^2), equipment (10.8 W/m^2) and people (one adult in the room, equivalent to 10.0m^2/workstation where 6(D)×3(W)=18) (ASHRAE 2005). Indoor temperature was set to 22.2 ℃ in the winter and 26.0℃ in the summer (KEMC, 2008). In addition, infiltration was set to 0.16 ACH with reference to (ASHRAE, 2005).

To simulate daylighting control, two photo sensors were set at two points 1.5 m and 4.5 m away from the window along the centreline of the room (Figure 2). 500 Lux was selected for general office work (IESNA, 2001). Each sensor, which is linked directly above fluorescent lighting located on the ceiling, operates as follows: If illuminance on the work space is above 500 Lux, the fluorescent light will be turned off. If not, the sensor provides enough electric energy to maintain 500 Lux in proportion (DOE, 2008).

EnergyPlus2.2 was selected for this study to simulate the room in Figure 2. To assess the dynamic control of interior and exterior blind systems, 'purchased air' was used to take into account the effect of the louver systems on the room energy use, isolated from other HVAC parameters .

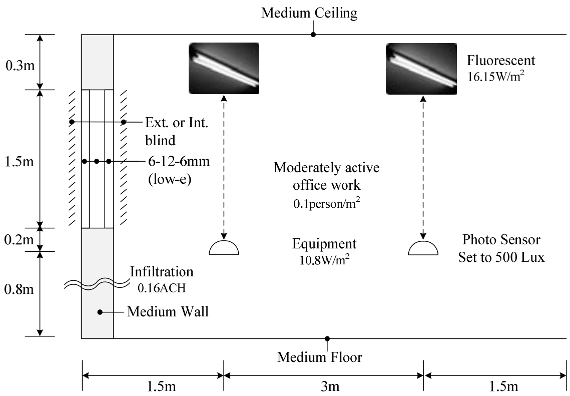


Figure 2 Simulation model

OPTIMAL CONTROL PROBLEM

Optimization for the blind systems can be achieved by determining the control variable that minimizes the cost function. The control variable is the blind slat angle (ϕ), while movement (lowered or retracted) of the blind is not considered in this study. The cost function (J, kWh/day) is expressed as a sum of f_1 (heating and cooling energy) and f_2 (lighting energy) during a sampling time, as shown in Equation (1). The slat angle is changed each hour of the day and the time horizon was 24 hours (one day). Thus, the hourly slat angle that minimizes the sum of the cost function (J) is determined by solving for the optimization problem as shown in Equation (1).

$$\min\ J = \sum_{k=1}^{24} [\, f_1(\phi) + f_2(\phi)]$$
$$s.t: 0^0 \le \phi \le 180^0 \qquad (1)$$

To deal with this nonlinear constrained optimization problem numerically, the function 'FMINCON', a MATLAB optimization routine, was employed. The function 'FMINCON' finds the minimum of a constrained nonlinear function of several variables starting at an initial estimate (Coleman et al, 1994). And it searches for optimal control variables in the iterative process as shown in Figure 3.

The iterative process is as follows: (1) based on the initial condition, a m-script file on MATLAB platform executes EnergyPlus.exe, (2) the m-file reads the simulation result from (*.csv), (3) then FMINCON function searches for better control variables and repeatedly overwrites *.idf (EngeryPlus input file) with driven control variables in the previous stage. If a convergence condition is met, the optimization problem process is terminated.

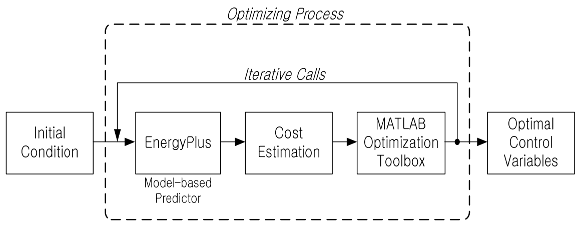


Figure 3 Optimization routine

OPTIMAL CONTROL SIMULATION

As deduced from Vine et al. (1998) and Reinhart (2001), there is no uniform pattern for the occupants to select the preferred blind slat angle. Thus, each of the following angles, 0°, 45°, 90°, and 135°, is assumed to be a manual blind slat angle (0°: horizontal, 0°-90°: outside slat-tip pointed to the sky, 91°-180°: outside slat-tip pointed to the ground). In addition to four manual cases, the basic case 'No blind' is included.

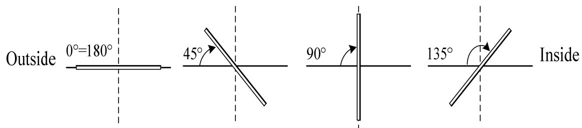


Figure 4 Angle of blind slat

The simulation runs were conducted under clear sky conditions (location: Seoul, Korea, summer: Jul. 26th, winter: Jan. 24th). The reason for clear sky is that the comparison of blind controls (manual vs. dynamic) under clear sky is more evident than under overcast sky.

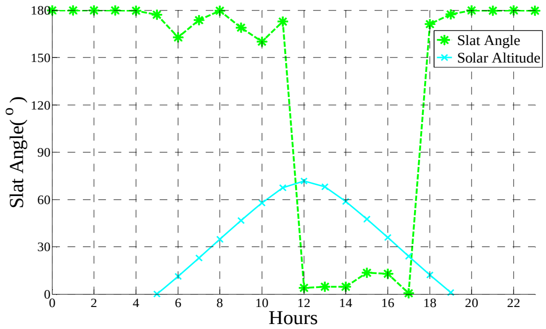
As shown in Table 1, it is clearly shown that that optimal control outperforms manual control, and the optimal slat angle is dependent on position (exterior vs. interior), solar altitude/azimuth and presence of daylighting autonomy.

Table 1 Energy consumption (kWh/day)

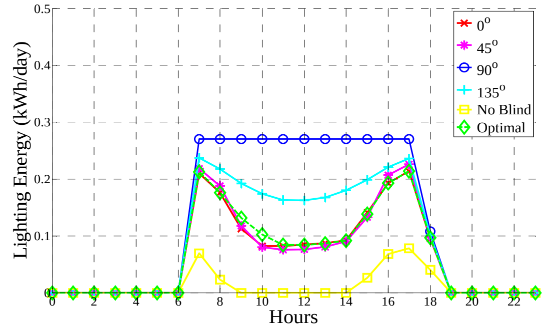
			Energy Use	No Blind	Manual Control 0°	45°	90°	135°	Optimal Control
E	S	DC	Cooling	6.7	5.0	5.1	4.0	4.7	4.9
			Heating	0.0	0.0	0.0	0.0	0.0	0.0
			Lighting	0.3	1.6	1.6	3.1	2.3	1.6
			Total	**7.1**	**6.6**	**6.6**	**7.1**	**6.9**	**6.5**
		NDC	Cooling	8.2	5.8	5.8	4.0	5.1	4.0
			Heating	0.0	0.0	0.0	0.0	0.0	0.0
			Lighting	3.1	3.1	3.1	3.1	3.1	3.1
			Total	**11.3**	**8.8**	**8.9**	**7.1**	**8.2**	**7.0**
	W	DC	Cooling	3.4	0.7	2.0	0.0	2.0	0.2
			Heating	4.2	5.6	4.7	9.0	4.7	5.8
			Lighting	0.7	1.6	2.1	3.1	2.1	1.7
			Total	**8.3**	**7.9**	**8.9**	**12.1**	**8.9**	**7.6**
		NDC	Cooling	4.3	1.1	2.4	0.0	0.0	0.3
			Heating	3.9	5.3	4.5	9.0	8.2	5.7
			Lighting	3.1	3.1	3.1	3.1	3.1	3.1
			Total	**11.2**	**9.5**	**10.0**	**12.1**	**11.3**	**9.1**
I	S	DC	Cooling	6.7	7.1	7.1	7.0	7.2	5.5
			Heating	0.0	0.0	0.0	0.0	0.0	0.0
			Lighting	0.3	1.7	1.8	3.1	2.3	1.7
			Total	**7.1**	**8.8**	**8.8**	**10.1**	**9.4**	**7.1**
		NDC	Cooling	8.2	7.8	7.8	7.0	7.6	6.2
			Heating	0.0	0.0	0.0	0.0	0.0	0.0
			Lighting	3.1	3.1	3.1	3.1	3.1	3.1
			Total	**11.3**	**10.9**	**10.8**	**10.1**	**10.7**	**9.2**
	W	DC	Cooling	3.4	4.0	4.0	3.8	4.0	4.2
			Heating	4.2	5.1	4.7	6.1	6.0	3.7
			Lighting	0.7	1.5	1.9	3.1	1.8	1.7
			Total	**8.3**	**10.7**	**10.6**	**13.0**	**11.8**	**9.6**
		NDC	Cooling	4.3	4.6	4.4	3.8	4.4	4.8
			Heating	3.9	4.9	4.6	6.1	5.7	3.4
			Lighting	3.1	3.1	3.1	3.1	3.1	3.1
			Total	**11.2**	**12.6**	**12.1**	**13.0**	**13.2**	**11.3**

E: Exterior, I: Interior, S: Summer, W: Winter, DC: Daylighting Control, NDC: No Daylighting Control

•*E-S-DC*: Optimal control shows a lowest energy use of 6.5 kWh/day, thus it could achieve an energy savings of 0.4 to 8.2% compared to manual control (Table 1). As shown in Figure 5(a), the optimal slat angle was around 0°-10° or 160°-180° which blocks direct solar radiation as well as allows daylighting to be reflected to indoor spaces (Figure 4). This optimal slat angle is similar to manual control (0°, 45°) in terms of effectively utilizing daylight. Manual control of 90° was expected to require the lowest energy use in a summer clear day since it would block direct and diffuse solar radiation all the day long, but it turns out the worst case because of electric lighting energy use and the heat dissipated from the lighting fixture. In other words, although the blind slat angles of 90° and 135° decrease cooling energy by means of blocking the solar radiation, lighting energy use and the heat from the fixture are increased due to decreased daylighting from the window.



(a) Optimal slat angle



(b) Lighting energy

Figure 5 E-S-DC Simulation results

•*E-S-NDC*: The result shows an energy savings of 0.6 to 26.6% (Table 1). As shown in Figure 6, the optimal slat angle is kept at 90° to block the solar radiation effectively during the day, but during the night, 0° (or 180°) angle is maintained to lower window temperature by means of thermal exchange (long-wave radiation) with the external environment. Manual control shows the effective slat angles to reduce energy use in orders of 90°, 135°, 0°, and 45°, respectively, in order of low solar radiation induction to high induction.

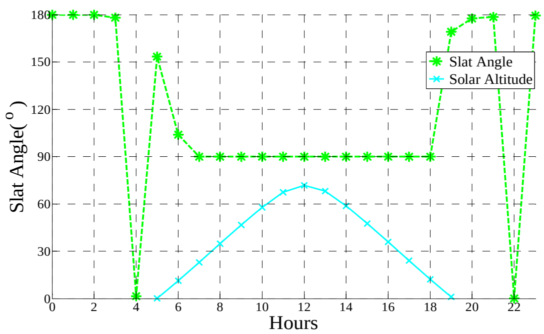
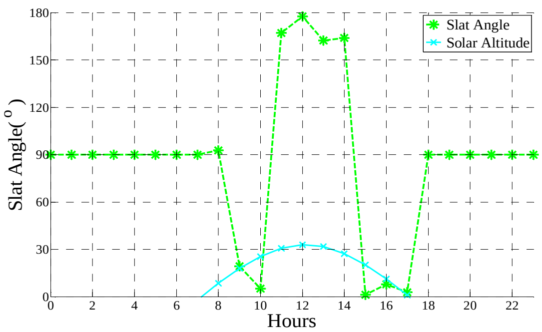


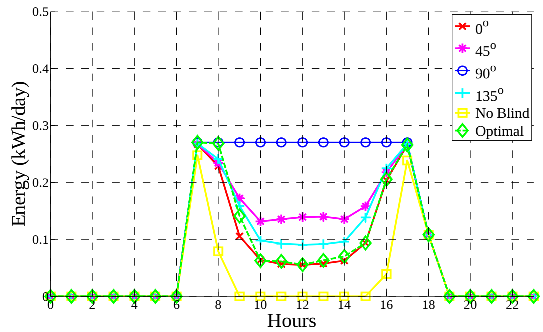
Figure 6 E-S-NDC Simulation result (slat angle)

•*E-W-DC*: Cooling load occurs even in the winter (Table 1), thus before and after sunrise and sunset, the heating and cooling pattern is changed e.g., around 10 a.m. from heating to cooling while around 5 p.m. from cooling to heating. As shown in Figure 7(a), the optimal slat angle is changed over 24 hours. First, the slat angle allows daylight to pass (9 to 10 a.m.) so as to reduce heating energy. Next, the slat angle blocks the solar radiation from 11 a.m. to 2 p.m. to reduce the cooling energy required. Finally, before sunset, the slat angle opens again to reduce heating energy during the night time by means of thermal storage effect. Because heating energy is a major component of total energy use (50-80%), thermal storage by the room component (wall, floor, ceiling, etc.) is important to reduce heating energy. During night time hours, the slat angle is set to 90° to decrease window heat loss via long-wave radiation between the surroundings and blind systems and, blind systems and glazing surface.

In the manual control case, it is better to set the blind slat slightly open (0°-20°) to allow daylight to enter the interior. Although the 90° slat angle achieves cooling energy savings by blocking all the solar radiation (cooling energy use = 0 kWh/day), it is the worst case for heating and lighting in terms of total energy use. On the contrary, the 0° shows the best performance for heating and lighting energy use, which are lowered to 4.9 kWh/day, in comparison with cooling energy use that requires a slight increase of 0.7 kWh/day (Table 1, Figure 7(b)).



(a) Optimal slat angle



(b) Lighting energy

Figure 7 E-W-DC Simulation results

•*E-W-NDC*: Similar to the case of E-W-DC, heating energy use of E-W-NDC represents a large portion of total energy use (50 to 70%), thus the optimal slat angle is similar to the case of E-W-DC (induction → blocking → induction within the 24 hour time horizon), resulting in an energy savings of 4.1 – 32.7% compared to manual control (Table 1). A 20% energy-use improvement is observed for 0° and 45° of manual cases allowing daylight to pass through the system in comparison with 90°. In addition, as mentioned in the section pertaining to E-W-DC, the thermal storage effect is used to reduce heating energy use. During night time hours, optimal slat angle is maintained at 90° to decrease window heat loss (Figure 8).

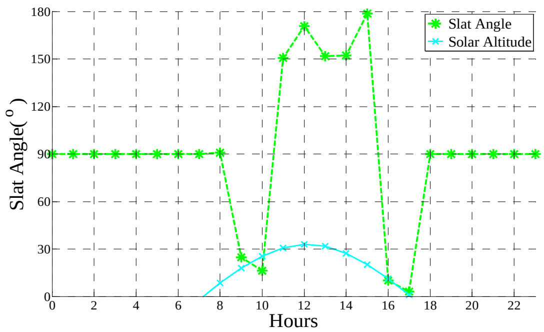
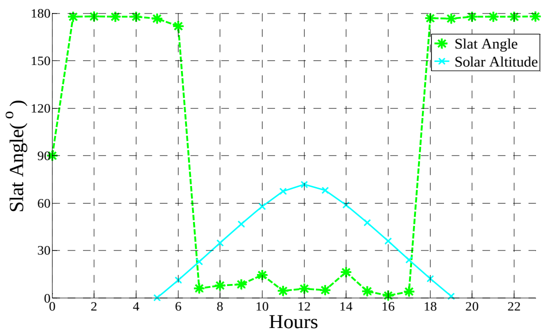
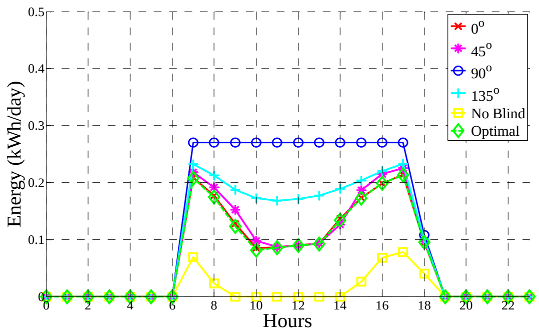


Figure 8 E-W-NDC Simulation result (slat angle)

•*I-S-DC*: Compared with manual control cases, optimal control can achieve a 22.9-41.1% energy savings (Table 1). As shown in Figure 9(a), the optimal slat angle is maintained at 0° to 20° (nearly horizontal) during the daytime, not only to block direct solar radiation, but also to maximize the advantage of daylighting control. Also, during the night time, the optimal slat angle is maintained at 180°(=0°) to cool indoor temperature using radiative heat exchange between the interior and exterior window surfaces. It is interesting that the 'No blind' result has almost the same value as the optimal case. This is because the daylight is supplied to the work plane sufficiently, thus lighting energy use and the resulting heat from the lighting fixture are minimized (Figure 9(b)). However, in the case of 'no blind', be noted that thermal discomfort due to asymmetric radiation (cold or hot glazing temperature) or discomfort glare can exist.



(a) Optimal slat angle



(b) Lighting energy

Figure 9 I-S-DC Simulation results

•*I-S-NDC*: The result shows that the slat blocks solar radiation during the daytime (150°-180°, Figure 10), and achieves energy savings of 9.1-18.2% compared with manual control cases (Table 1). In the case of no blind, there is a distinct difference compared with I-S-DC, because it cannot utilize the daylighting autonomy.

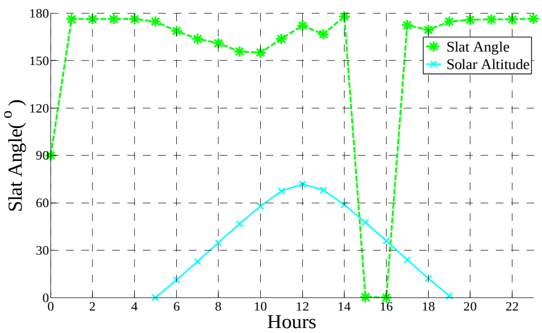
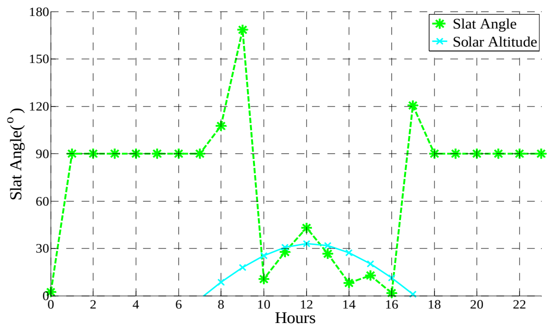


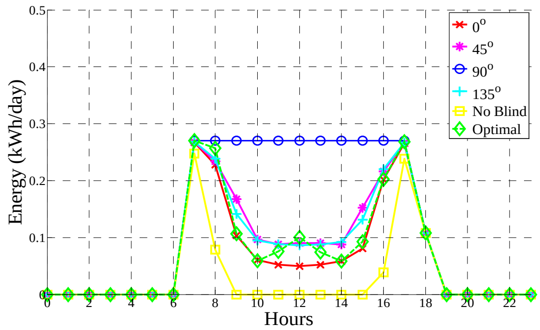
Figure 10 I-S-NDC Simulation result (slat angle)

•*I-W-DC*: There is an energy savings of 10.4-35.2% with I-W-DC compared to manual control (Table 1). As shown in Figure 11(a), optimal slat angle follows solar altitude to maximize the daylight. The most effective way to reduce the solar load on fenestration is to intercept direct radiation from the sun before it reaches the glass (ASHRAE 2005). In case of interior blinds, solar radiation passing through the window is distributed on internal surfaces (wall, floor, ceiling, slats, furniture), and the effect of blocking solar radiation is not significant compared to the exterior blind (ASHRAE 2005). Thus, the use of daylighting control has more advantages than internally shading the direct solar radiation which reaches the interior glazing of a window (Figure 11(a), (b), Table 1).

In order to minimize thermal radiation (or convection) from interior to exterior, the optimal slat angle is maintained at 90° during the night time. However, it should be noted that that 'No blind' performs better than optimal control since lighting operation time is shortened and cooling energy requirements are reduced (Table 1).



(a) Optimal slat angle



(b) Lighting energy

Figure 11 I-W-DC Simulation results

•*I-W-NDC*: Optimal control can achieve energy savings of 6.7%-16.9% compared with manual/no blind, except with respect to lighting energy (Table 1). Thus, compared to I-W-DC, overall energy use increased by 1-2 kWh/day with I-W-NDC. Moreover, because the advantages of thermal storage effect far outweigh the reduction of cooling energy by blocking solar radiation, thus most solar radiation is not shaded (Figure 12). During night time, heat loss via long-wave radiation exchange is minimized by keeping slat angle at 90°.

It is interesting that the heating energy use of optimal control is lower than that of 'No blind'. Although 'No blind' acquires more daylight (solar radiation) during the daytime, it loses more energy during night time because of radiant heat exchange to surroundings. It can be inferred that interior blinds can act as a radiation shield.

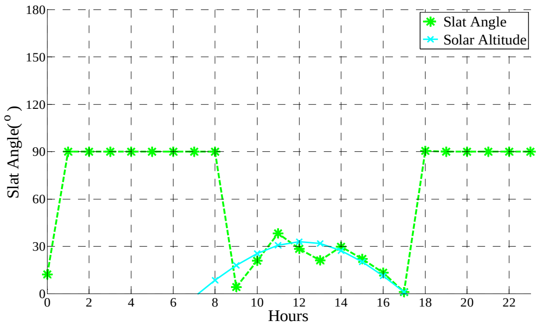


Figure 12 I-W-NDC Simulation result (slat angle)

Analysis of daylighting control

As shown in Table 2, DC is 'always' advantageous compared to NDC, regardless of the presence of slat angle or optimal control. With daylighting control, allowing enough daylighting, resulting in the reduction of lighting energy as well as heat dissipation from the fixture is always more beneficial than blocking solar radiation for sake of avoiding transmitted solar radiation. Hence, the slat angle for providing proper daylight to the work plane (0°-20°) is strongly recommended regardless of season when DC is applied.

Without daylighting control, there is no reduction of lighting energy use, resulting in increase of total energy use (1.2-4.2 kWh/day) (except for 90°, Table 1). Consequently, the blind operation should be changed according to the presence of daylighting control. Moreover, it should be noted that '*manual slat control with daylighting control*' achieves better performance than '*optimal slat control without daylighting control*'.

Analysis of seasonal variation

Heating and cooling modes occur in a winter day. Because the solar radiation energy stored in the room structure during the daytime is released to the room during the night time, heating energy can be saved (induction→interception→induction). Hence, it is necessary for the blind systems to change its operation according to the heating and cooling mode.

'No blind' in Table 1 shows the lowest energy consumption in the winter. This is because a considerable amount of solar radiation from the window leads to a significant reduction in the heating energy use.

In the summer season, there is a difference in energy use according to the presence of daylighting control and slat angle control. In general, it is recommended to have a slat angle to intercept direct solar radiation and to induce diffuse solar radiation when daylighting control is present. At night time, the optimal slat angle varies according to the heating and cooling mode, (winter: 90°, summer: 0°) for exterior and interior blinds. This is relevant to controlling long-wave radiation exchange between the inside and outside.

Analysis of blind position

The most effective way to reduce the solar load on fenestration is to intercept direct radiation from the sun before it reaches the glass (ASHRAE, 2005). Table 3 shows an exterior blind energy use of approximately 77-83% compared to an interior blind; averages are shown for all manual controls and optimal control. For this reason, it should be noted that the blind position is one of the important energy saving factors. Consequently, as deduced from Tables 1 and 3, 'the position (exterior vs. interior)' is more influential to energy saving than 'application of optimal control'.

CONCLUSION AND FUTURE WORK

The paper compares the optimal control with manual control of blind systems. The optimal control finds control variables that reflect the system response during the time horizon and the time-lag effect by thermal inertia. In this study, optimal control of the blind slat angle was developed integrating the EnergyPlus room model of an optimization routine in the MATLAB optimization toolbox. The optimal control simulation runs were made for different seasons (summer/winter), blind position (interior/exterior), and daylighting control (with vs. without).

It was found that optimal control of blind systems outperforms manual control due to activating slats and artificial lighting (on/off). The energy performance of blind systems can be significantly improved by applying daylighting control. In other words, '*manual control with daylighting control*' can perform better than '*optimal control with no*

Table 2 Total energy use (DC vs. NDC)

		Equation	No blind	Manual control				Optimal control	Average
				0°	45°	90°	135°		
E	S	DC/NDC	7.1/11.3=**0.63**	6.6/8.8=**0.74**	6.6/8.9=**0.75**	7.1/7.1=**1.00**	6.9/8.2=**0.85**	6.5/7.0=**0.93**	**0.81**
	W	DC/NDC	8.3/11.2=**0.74**	7.9/9.5=**0.83**	8.9/10.0=**0.88**	12.1/12.1=**1.00**	8.9/11.3=**0.78**	7.6/9.1=**0.84**	**0.85**
I	S	DC/NDC	7.1/11.3=**0.63**	8.8/10.9=**0.80**	8.8/10.8=**0.82**	10.1/10.1=**1.00**	9.4/10.7=**0.88**	7.1/9.2=**0.77**	**0.82**
	W	DC/NDC	8.3/11.2=**0.74**	10.7/12.6=**0.85**	10.6/12.1=**0.88**	13.0/13.0=**1.00**	11.8/13.2=**0.89**	9.6/11.3=**0.85**	**0.87**

Table 3 Total energy use (Exterior vs. Interior)

		Equation	No blind	Manual control				Optimal control	Average
				0°	45°	90°	135°		
S	DC	E/I	n/a	6.6/8.8=**0.75**	6.6/8.8=**0.75**	7.1/10.1=**0.70**	6.9/9.4=**0.74**	6.5/7.1=**0.92**	**0.77**
	NDC	E/I	n/a	8.8/10.9=**0.81**	8.9/10.8=**0.82**	7.1/10.1=**0.70**	8.2/10.7=**0.77**	7.0/9.2=**0.76**	**0.77**
W	DC	E/I	n/a	7.9/10.7=**0.74**	8.9/10.6=**0.84**	12.1/13.0=**0.93**	8.9/11.8=**0.75**	7.6/9.6=**0.80**	**0.81**
	NDC	E/I	n/a	9.5/12.6=**0.75**	10.0/12.1=**0.83**	12.1/13.0=**0.93**	11.3/13.2=**0.85**	9.1/11.3=**0.81**	**0.83**

daylighting control'(except for 90°). In the case of daylighting control, a horizontal slat angle of around 0° is the best for energy savings, regardless of the season. It can be said that daylighting control is not an option but a necessity for purpose of energy saving. In addition, the blind position is important to reduce building energy use; '*an exterior blind with manual (or static) control*' can perform better than '*an interior blind with optimal control*'. Careful integration of the three factors (seasons, position, and daylighting control) and operation of blind systems can help blind systems act as a true energy saver as well as environmental controller.

Following the successful development of optimal blind control and its implementation, future studies may include: (1) optimal design (width, depth, distance from window, property (reflectance), etc., (2) application of optimal control to a real system, (3) integration of blind optimal control with central building HVAC system.

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