Model Predictive Control of Integrated Room Automation Considering Occupants Preference

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***Abstract*—A framework for the simultaneous control of temperature, illumination and window roller blind position is considered. The occupants are allowable to adjust their comfort preference to a strict, mild or loose level. The cost function has two parts including energy consumption and comfort dissatisfaction, each of which is expected to be minimized based on the users' comfort settings. The control strategy is Model Predictive Control (MPC) and it computes a trajectory of future manipulated variables to optimize future room temperature, illumination and outside view along with the minimum possible departure from the desired level. Weather data like solar radiation, solar illumination and outside temperature are considered in the model with the aim of taking advantage of daylight without disrupting other comfort levels. Simulation analyses were performed for the summer and winter days revealing the influence of the roller blind position on the building total energy consumption. The simulation results affirm that the proposed model can save energy by minimally changing occupants' comfort requirements during some hours of the day.**

I. Introduction

The implementation of smart building projects worldwide has increased consumers' contribution in demand response and building energy management. Enforcing an energy-saving policy manually is a tedious procedure for the user while automatic demand response approaches allow energy curtailment without user intervention. Recent studies have shown that about 13% and 30% of electricity consumption is for lighting and space conditioning purposes, respectively [1]. Daylight in spaces increases occupant satisfaction and improves worker productivity and can be controlled by roller blind position [2]. Accordingly, it is important to consider building thermal and lighting capacity in energy conservation while ensuring occupant satisfaction of the comfort level of the building temperature and light.

Various control approaches have been presented considering the energy saving potential of a household's appliances, lighting and thermal system [3], [4]. In [5], the author considered the minimum and maximum illumination requirements depending on the type of usage mentioned in the existing lighting standards and proposed a systematic optimization-based approach to assess the demand response capacity of automatic lighting control systems. In [6], a fuzzy controller for the corresponding positioning of roller blinds with the available solar radiation was developed and designed to assure the desired inside illumination. Predictive control has a high potential to be exploited in integrated room automation and it is currently considered by most researchers. For instance, a model predictive control strategy was used in [7] and [8] making use of the weather forecast to keep the room temperature within the comfort level. In [9], the inherent flexibility of HVAC systems in commercial buildings for cooperation with utilities was investigated while the temperature was maintained within the desired boundary.

There are several factors that necessitate developing integrated control of thermal units, lighting systems and roller blinds. First, consider the daylight effect in advancing the occupants working performance and respecting their desire to see the scene outside the window. Second, motivating end-users to save energy and collaborate with the utility, particularly during peak demand, while their comfort level is guaranteed not to be violated significantly. During these hours the building energy management system may offer some flexibility to the utility in terms of how much energy it can save. Thus, the main focus of this paper is to characterize fundamental trade-offs between energy savings and consumer satisfaction of comfort, taking into account outside weather data and the occupant's setting of comfort enjoyment, which is specified in three different levels, titled strict, mild and loose comfort satisfaction. Selecting the desired adjustment, the proposed control system can provide complete satisfaction of comfort for the user without taking into consideration energy saving in strict mode, or it can save some energy by slightly deviating from the comfort level in either the mild or loose mode. Under all conditions, the amount of comfort deviation is expected not to be very large to give the user adequate motivation to save energy.

The rest of the paper is organized as follows. The system model is presented in section II. Section III describes the control architecture and our proposed solution approach. In section IV, we present our proposed mathematical model and cost function using MPC. Simulation results are compared in section V. The paper ends with conclusions and future works in section VI.

II. System Model

In this part, we consider a single room thermal dynamic model involving a cooling or heating unit along with the lighting system and specify the relationship between the roller blind position and the indoor temperature and illumination.

A. Cooling and Heating Systems Model

Solar radiation directly from the sun or indirectly from the sky and surroundings reaches the window. The radiation absorbed by the window is released as heat to the indoor environment and influences the inside temperature. The temperature evolution dynamic equation based on empirical studies is given by [10]:

$$T^{k+1} = T^k - a(T^k - T^k_{out}) + mbP^k_{hc} + w^k, \qquad (1)$$

TABLE I
NOTATIONS

Symbol	Description
T^k	inside temperature at hour k
T^k_{out}	outside temperature at hour k
I^k	total illumination at each point at hour k
V^k	outside view at hour k
P^k_{hc}	cooling or heating unit Power consumption at hour k
P^k_i	light source i power consumption at hour k
P_{hcmax}	cooling or heating unit maximum Power consumption
P_{imax}	light source i maximum power consumption
τ_r	window solar radiation transmittance
τ_l	window solar illuminance transmittance
A_w	window area
A_r	room area
Q^k_s	solar radiation at hour k
L^k_s	daylight illumination at hour k
m	constant(+1 for heating and -1 for cooling unit)
C	thermal capacitance of building
R	thermal resistance of building
η	cooling or heating system efficiency
ϕ^k	daylight factor at hour k
M	dirt correction factor
d_w	radial distance from window
d_i	radial distance from light source i
x_i	horizontal distance from light source i
y_i	vertical distance from light source i
r^k	roller blind position at hour k

where thermal equation parameters are listed in TABLE I for further elaboration. The incoming solar heat gain through the window denoted by w^k is a type of disturbance that can influence the system based on seasonal solar radiation Q^k_s and it is characterized by $w^k = \frac{\tau_r A_w Q^k_s}{C}$ [11]. The amount of solar radiation heat entering the room is dependent on the position of the roller blind. Thus, A_w in w^k is replaced by $w^k = \frac{\tau_r(100-r^k)A_w Q^k_s}{100C}$. The insulation parameter a is expressed in terms of thermal resistance R and thermal capacitance C of the building and it is defined by $a = \frac{1}{RC}$. The efficiency of cooling or heating unit η impacts parameter b in (1), which is specified by $b = \frac{\eta}{C}$.

B. Lighting System Model

Illumination intensity at each point in the room is estimated depending on the candle power of the lighting bulbs, their location in the building, direction of their light concentration and the amount of daylight from outside that enters a building through the windows. The focus of our attention in this paper is recessed light which has light shining in a downward direction. Considering N dimmable light bulbs in the room, an extension of illumination calculation of each point in the room at hour k

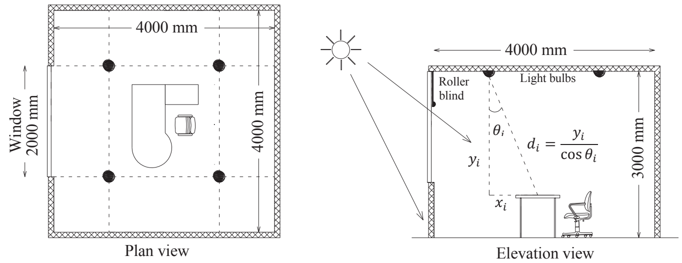

Fig. 1. The plan and elevation view of a room. Light bulbs are shown with black circles. Natural daylight enters the room through the side window.

is determined by [5]:

$$I^k = \sum_{i=1}^{N} \frac{\alpha_i y_i}{(x_i^2 + y_i^2)^{1.5}} P^k_i + \beta + \gamma^k, \tag{2}$$

$$\beta = \sum_{i=1}^{N} \frac{\beta_i y_i}{(x_i^2 + y_i^2)^{1.5}}, \tag{3}$$

The parameters of the lighting equations are listed in TABLE I. y_i and x_i are the vertical and horizontal distance from light source i, as shown in Fig. 1. Parameters α_i and β_i are based on relative light output versus relative input power for a dimming lamp. For a typical T-8 fluorescent, α_i and β_i equal 0.89 and 14.87, respectively [5]. Natural daylight γ^k depends on window solar illuminance transmittance τ_l, daylight factor ϕ^k and daylight illumination L^k_s at hour k, and it is measured by $\gamma^k = \tau_l \phi^k L^k_s$. The daylight factor ϕ in percentage depends on the area of the room, window and the building geographical location. Different methods have been proposed to calculate the value of ϕ [12], [13]. In this paper, we used the approximate daylight calculation that is not location dependent and its average value is defined by $\phi = \frac{52MA_w}{A_r}$, where M is the correction factor for dirt on the window and takes a value of between 0 and 1 [14]. The total surface area of the room A_r includes the ceiling, floor, walls and windows surfaces. The window area is defined by A_w, taking account framing. It is expected that changing the position of the window roller blind affects the value of the daylight factor and the amount of light entering through the window. Thus, ϕ^k should be scaled according to the roller blind position as follows:

$$\phi^k = \frac{52M(100-r^k)A_w}{100A_r}, \tag{4}$$

Roller blind position is shown by r^k and it changes between 0, meaning fully open, to 100, meaning fully closed. The above-mentioned daylight factor is for areas very close to the window and it decreases with distance. Considering the sunlight on the window glazing is like a light source, total daylight is approximately estimated by $\gamma^k = \frac{\tau_l \phi^k L^k_s}{d_w^2}$, which decreases by the inverse square of the distance from the window denoted by d_w. For simplicity, we assume that all light bulbs in the room have a similar maximum intensity and power consumption. We also assume P^k_i is the same for all light fixtures in the room. Thus, from now on we replace P^k_i by P^k_l as each individual

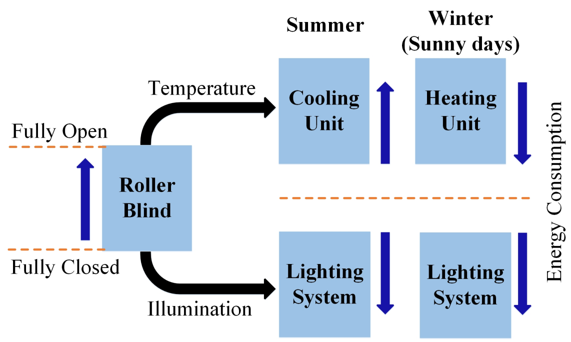

Fig. 2. Roller blind position effect on cooling/heating unit and lighting system energy consumption in summer and winter

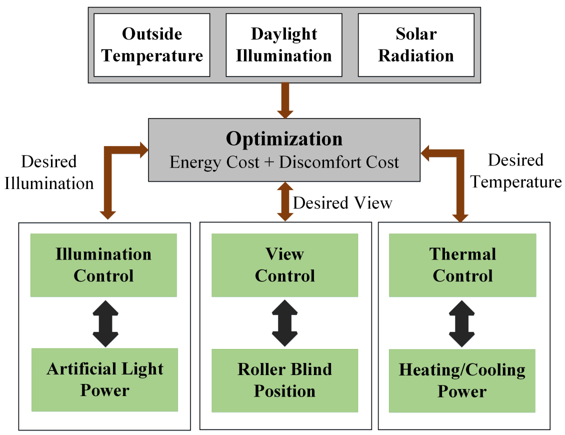

Fig. 3. Control architecture of temperature, illumination and view

light source power consumption. Putting this assumption in (2) leads to the following light equation.

$$I^k = \alpha P_l^k + \beta + \tau_l \frac{52M(100 - r^k)A_w}{100 A_r d_w^2} L_s^k, \tag{5}$$

where α is defined by $\alpha = \sum_{i=1}^{N} \frac{\alpha_i y_i}{(x_i^2+y_i^2)^{1.5}}$.

III. Integrated Control Architecture

Due to the dependency of inside temperature and light on the area of the window, our aim is to control the position of the roller blind, cooling/heating unit and lighting power consumption simultaneously to reduce the total energy cost while respecting consumers' comfort level in the building. Figure 2 demonstrates the seasonal relationship between the roller blind position and the lighting and cooling/heating power consumption. Solar heat gain and daylight intensity inside the room change based on the roller blind position. In hot weather conditions, uncovering the window has a positive contribution to the illumination controller while increasing the cooling unit energy consumption. In contrast, during sunny days in the winter, uncovering the window has a positive contribution to the inside thermal control and additionally leads to less artificial lighting energy consumption. Figure 3 shows the architecture for the concurrent control of room illumination and temperature as well as the roller blind position to maintain the preference of having an outside view. Based on the current measurements of weather data and its predictions during the next hours, the cost function comprising of both energy consumption and comfort dissatisfaction should be minimized.

IV. Mathematical Model

In this section, we delineate the mathematical modeling of the integrated room control system and define an optimization problem with the objective of the energy saving and comfort satisfaction. Assume at hour k, the occupant wants to keep the indoor temperature and illumination at $\hat{T}^k$ and $\hat{I}^k$, respectively. Thus, the deviations of measured temperature and illumination from the desired levels justify occupant's discomfort. Another objective is to provide sufficient outside view and daylight for the occupants to achieve their satisfaction. Occasionally, the user might expect the window to be fully uncovered together with the inside illumination and temperature to be as close to the target level as possible, which means there is no concerns regarding the energy payment. In another scenario, the user might prefer to slightly sacrifice the desired level of illumination, temperature or outside view for a lesser electricity bill. To formulate the mathematical objective, the state space modeling of the system is first introduced in the following.

A. State Space Modeling

The state space illustration of a discrete time system is given as

$$X_{k+1} = AX_k + B_k U_k + W_k, \tag{6}$$

where X_k and U_k are the state input and controller input vector at time slot k, respectively. The exterior disturbance is another input variable of the system and it is represented by W_k. Using (1) and (5), the state evolution of temperature, illumination and outside view of the building is linearly determined as follows:

$$\underbrace{\begin{bmatrix} T^{k+1} \\ I^{k+1} \\ V^{k+1} \end{bmatrix}}_{X_{k+1}} = \underbrace{\begin{bmatrix} 1-a & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}}_{\text{A}} \underbrace{\begin{bmatrix} T^k \\ I^k \\ V^k \end{bmatrix}}_{X_k} + \tag{7}$$

$$\underbrace{\begin{bmatrix} 0 & mb & -\mu_1 Q_s^k \\ \alpha & 0 & -\mu_2 L_s^k \\ 0 & 0 & 1 \end{bmatrix}}_{B_k} \underbrace{\begin{bmatrix} P_l^k \\ P_{hc}^k \\ r^k \end{bmatrix}}_{U_k} + \underbrace{\begin{bmatrix} aT_{out}^k + 100\mu_1 Q_s^k \\ \beta + 100\mu_2 L_s^k \\ 0 \end{bmatrix}}_{W_k},$$

where μ_1 and μ_2 are specified by $\mu_1 = \frac{\tau_r A_w}{100C}$ and $\mu_2 = \frac{52MA_w\tau_l}{100A_r d_w^2}$. As can be seen in (7), U_k includes lighting system power consumption P_l^k, thermal unit power consumption P_{hc}^k and roller blind position r^k as control inputs. The status vector X_k consists of temperature T^k, illumination I^k and outside view V^k in which, the latter status only depends on the roller blind position r^k.

B. Cost Function

Linear Quadratic MPC is used as a cost function to be minimized with the aim of reducing the energy consumption and user comfort dissatisfaction. In general MPC is an online optimization technique taking the latest information into consideration and performing the optimization in real time with a moving horizon time window. The finite horizon cost function is defined by

$$\tilde{H}_k = \sum_{j=0}^{J-1}[(X_{k+j} - \hat{X}_{k+j})^T \mathcal{G}_1 (X_{k+j} - \hat{X}_{k+j}) + FU_{k+j}] + (X_{k+J} - \hat{X}_{k+J})^T \mathcal{G}_2 (X_{k+J} - \hat{X}_{k+J}), \tag{8}$$

where $\tilde{H}_k$ is a linear quadratic problem starting at time k and it presents optimizing sequences of control inputs for current and future J time steps. k moves over the total span of interest that might be equal to or larger than J. The linear and the quadratic parts are related to the energy cost and states deviation from desired level, respectively. The occupant's desired temperature, illumination and outside view are defined in $\hat{X}$ and it can be renewed by the moving of the horizon time window. Penalty factors of desired states violation are defined in $\mathcal{G}_1$ and $\mathcal{G}_2$, which are symmetric positive definite matrices. The penalty p for energy consumption is part of a row vector F.

$$\mathcal{G}_1 = \begin{bmatrix} \delta & 0 & 0 \\ 0 & \mu & 0 \\ 0 & 0 & \vartheta \end{bmatrix}, \mathcal{G}_2 = \begin{bmatrix} \acute{\delta} & 0 & 0 \\ 0 & \acute{\mu} & 0 \\ 0 & 0 & \acute{\vartheta} \end{bmatrix}, F = \begin{bmatrix} p & p & 0 \end{bmatrix},$$

Based on equation (6) and the current state X_k, future states over the prediction horizon satisfy [15]:

$$\mathbf{X}_k = \Lambda X_k + \Phi_k \mathbf{U}_k + \Theta \mathbf{W}_k, \tag{9}$$

$\mathbf{U}_k \in \mathbb{R}^{3J \times 1}$ is the control input vector during J prediction horizon and $\mathbf{X}_k \in \mathbb{R}^{3J \times 1}$ is its equivalent state vector starting at time slot k. $\mathbf{W}_k \in \mathbb{R}^{3J \times 1}$ consists of disturbance at each time slot within the prediction horizon specified as follows:

$$\mathbf{X}_k = \begin{bmatrix} X_{k+1} & X_{k+2} & . & . & . & X_{k+J} \end{bmatrix}^T,$$
$$\mathbf{U}_k = \begin{bmatrix} U_k & U_{k+1} & . & . & . & U_{k+J-1} \end{bmatrix}^T,$$
$$\mathbf{W}_k = \begin{bmatrix} W_k & W_{k+1} & . & . & . & W_{k+J-1} \end{bmatrix}^T,$$

We introduce matrices $\Phi_k \in \mathbb{R}^{3J \times 3J}$, $\Theta \in \mathbb{R}^{3J \times 3J}$ and $\Lambda \in \mathbb{R}^{3J \times 3}$ in this way.

$$\Phi_k = \begin{bmatrix} B_k & 0 & . & . & . & 0 \\ AB_k & B_{k+1} & . & . & . & 0 \\ . & . & . & & & . \\ . & . & & . & & . \\ . & . & & & . & . \\ A^{J-1}B_k & A^{J-2}B_{k+1} & . & . & . & B_{k+J-1} \end{bmatrix},$$

$$\Lambda = \begin{bmatrix} A \\ A^2 \\ . \\ . \\ . \\ A^J \end{bmatrix}, \Theta = \begin{bmatrix} I & 0 & . & . & . & 0 & 0 \\ A & I & . & . & . & 0 & 0 \\ . & . & . & & & . & . \\ . & . & & . & & . & . \\ . & . & & & . & . & . \\ A^{J-1} & A^{J-2} & . & . & . & A & I \end{bmatrix},$$

Hence, (8) is simplified in the following vector form and it is solved repeatedly by the controller starting from time slot k.

$$\begin{aligned} \underset{\mathbf{U_k}}{\textbf{minimize}} \quad & (\mathbf{X}_k - \hat{\mathbf{X}}_{\mathbf{k}})^T \mathbf{G} (\mathbf{X}_k - \hat{\mathbf{X}}_{\mathbf{k}}) + \mathbf{F}\mathbf{U}_k && (10) \\ \textbf{subject to} \quad & \mathbf{X}_k = \Lambda X_k + \Phi_k \mathbf{U}_k + \Theta \mathbf{W}_k && (11) \\ & |\mathbf{X}_k - \hat{\mathbf{X}}_{\mathbf{k}}| \leq \Upsilon_{max} && (12) \\ & \mathbf{U}_{min} \leq \mathbf{U}_k \leq \mathbf{U}_{max} && (13) \end{aligned}$$

$\mathbf{G} \in \mathbb{R}^{3J \times 3J}$ and $\mathbf{F} \in \mathbb{R}^{3J \times 1}$ are respectively defined by $\mathbf{G} = \text{diag}(\mathcal{G}_1, ..., \mathcal{G}_1, \mathcal{G}_2)$ and $\mathbf{F} = \begin{bmatrix} F & F & ... & F \end{bmatrix}$. constraint (11) is a simplified state space modeling of the building that demonstrates how the current states, control inputs and weather condition affect the states in future time steps. The maximum allowed deviation of states from the desired level is specified in constraint (12). Control inputs are allowed to change within a range that is binded in constraint (13). Disturbance vector $\mathbf{W}_k$ is assumed to be constant during the J step control moves calculation but it can be updated during each receding horizon optimization. Hourly climate information and current states of the inside temperature and illumination are assumed to be measured and predicted by specific roof top and indoor sensors. Based on the penalty factors, the best deviation for temperature, illumination and outside view as well as optimum control inputs $\mathbf{U}_k$ are obtained for the current time while taking account future time slots. However, only the result of the current time slot is implemented. k moves to the next sampling instant and the optimization is re-done.

V. Performance Evaluation

A. System setup

To evaluate the performance of the MPC model, a type of office space, for example a room with four 96 watt T-8 fluorescent lamps, is considered. Figure 1 shows the plan and elevation view of the room, the positions of artificial lights and a working desk in the middle of the room. We assume that one cooling and heating system with a maximum power consumption of 6.5 kW is installed in the room and all the lights have the same input power. Numerical values of lighting and thermal unit parameters are summarized in Table II.

TABLE II
TYPICAL PARAMETER VALUES USED IN SIMULATION [17]

Parameter	Value Range	Unit
P_{imax}	96	W
τ_l	0.48	
A_w	4	m^2
A_r	56	m^2
M	1	
C	1.5-2.5	kWh/°C
R	1.5-2.5	°C/kW
τ_r	0.5	
η	2.5	
P_{hcmax}	6.5	kW

A typical office space of 4m × 4m × 3m with a 2m×2m window is considered with no obstructions in the front. The problem is solved under a clear sky condition for a day in summer and a sunny day in winter. Neglecting the influence of seasons on the sunrise and sunset time, the average value of solar radiation Q_s^k and daylight illumination L_s^k at time k is considered to be a quadratic function [16] and it is represented by:

$$Q_s^k = \begin{cases} Q_{smax}(-\frac{1}{36}k^2 + \frac{2}{3}k - 3) & 6 \leq k < 18 \\ 0 & 0 \leq k < 6, 18 \leq k < 24 \end{cases}$$

Maximum solar radiation Q_{smax} and daylight illumination L_{smax} are assumed to be 1000 W and 10000 Lux on a sunny day in summer while they are reduced to 500 W and 8000 Lux in winter.

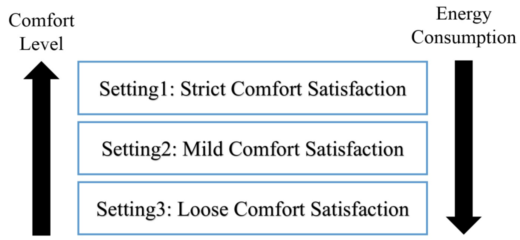

Fig. 4. Comfort satisfaction and energy saving for knobs adjustments

TABLE III
TOTAL ENERGY CONSUMPTION AND APPROXIMATE MAXIMUM STATES VIOLATION FOR FIXED COMFORT SETTING IN A DAY

Setting mode	Total energy consumption in a day (kWh)	ΔT (°C)	ΔI (Lux)	ΔV (%)
Strict	64.5	0	0	0
Mild	58.9	0.5	60	≤ 50
Loose	51.7	1	120	100

B. Scenarios and simulation results

The simulation is based on a 24 hour prediction horizon for a day in summer and a sunny winter day. A fixed price p is assumed during the whole day. Three knobs are defined for the occupants to change their comfort satisfaction level of temperature, light and roller blind position. Each knob has three setting levels including strict, mild and loose. δ, μ and ϑ penalty factors are automatically modified based on the consumer's knob settings to either minimize the energy consumption or provide for their comfort. It is clear that for strict comfort satisfaction the penalty factors have the highest values compared with mild and loose adjustments. Figure 4 indicates the inverse relationship between comfort satisfaction level and its equivalent level of power consumption.

The problem is a convex optimization problem under linear constraint and it is solved by MATLAB CVX software. The maximum allowable deviations from the desired levels is defined in constraint (12). For room temperature, it is bounded to a maximum value of 2. Based on the lighting standard, the required level of illumination of each space depends on the task type. In an office building, at least 600 Lux should be provided on each working desk. However, studies have shown that people are insensitive to a luminance changes of 20% and are willing to accept an illumination change of up to 30% [18] which can be used as an acceptable deviation of illumination level from the desired value. Figure 5 shows how the room temperature, illumination and roller blind position deviate from the set points under different settings of the knobs during a day in summer. Since solar radiation and illumination are zero at night and their effect is negligible on cost minimization, the roller blind tends to be positioned at the desired level which is presumed to be zero in the simulation. Under loose comfort satisfaction during the day, the roller blind position is 100, meaning fully closed, to eliminate solar radiation disturbance. Similar analyses were conducted for the winter case.

As can be seen in Figure 6, on a sunny winter day the roller blind position tends to be 0, meaning fully uncovering the window under loose adjustment of comfort satisfaction. For a better explanation of roller blind position, the desired level of outside view is assumed to be 50 for the whole day. The results for sunny winter case affirm the positive contribution of the open roller blind in saving energy, which was illustrated in Figure 2. We also performed analyses for the same day under the fixed setting of either strict, mild or loose for the whole day to figure out the energy saving flexibility of the system. For comparison, the total energy consumption related to the cooling unit and light bulbs along with maximum deviation of temperature, illumination and outside view from their desired level are summarized in Table III. Simulation results indicate a mild setting leads to around the 8% energy saving per day compared with the strict mode, while the maximum comfort violation is around 0.5 °C for temperature and 60 Lux for illumination. Also, a loose setting leads to around a 19% energy saving per day compared with the strict mode, while the maximum comfort violation is around 1 °C for temperature and 120 Lux for illumination. Figure 7 shows the relationship between the price sensitivity of the user and comfort dissatisfaction. As can be seen, the higher the price is, the more temperature and illumination violate to minimize both energy and discomfort cost.

VI. CONCLUSIONS AND FUTURE WORKS

We presented a Model Predictive Control approach for the integrated control of light, temperature and roller blind position in a room with the aim of energy saving while considering the satisfaction of the occupant's preferences. We defined three types of comfort settings for the occupants- strict, mild and loose comfort satisfaction, which will directly affect the power consumption. Under the proposed control model, each of the cooling/heating unit and lighting power consumptions along with the roller blind position are expected to act at their optimum points each time while the minimum offset of temperature and illumination from users' desired levels is calculated. The advantage of such a centralized control system is that it can minimize the total cost in terms of both energy and discomfort at a given time based on whether the occupant prefers to pay less for energy consumption, even under a slight violation of comfort level, or the occupant desires the comfort level to be completely satisfied for a greater energy payment. For an extension and possible future work direction, one can consider a large scale building with the integrated control system. Another extension involves uncertain model considering the inherent uncertainty of the weather predictions.

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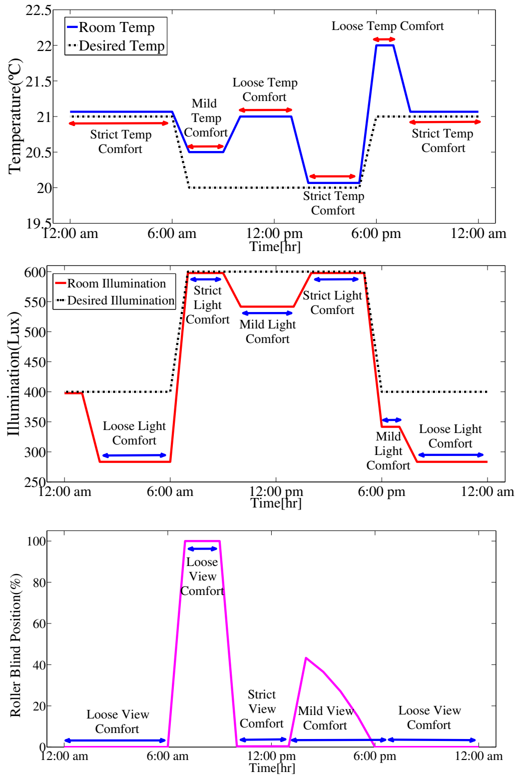

Fig. 5. Temperature, Illumination and Roller blind position deviation from desired level under different comfort settings on a clear sky day in summer

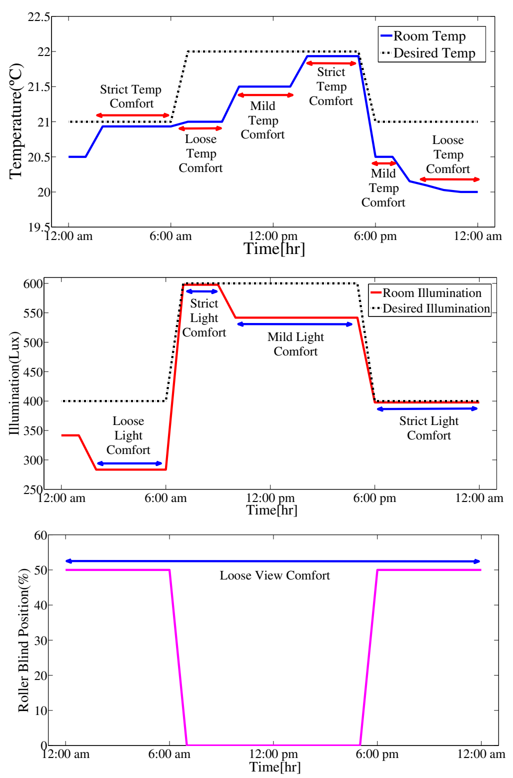

Fig. 6. Temperature, Illumination and Roller blind position deviation from desired level under different comfort settings on a sunny day in winter

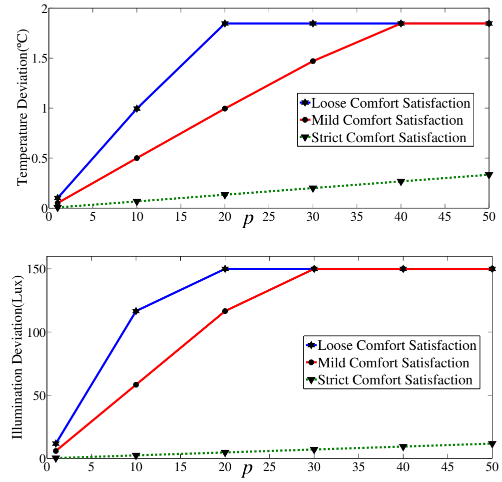

Fig. 7. Room temperature and illumination deviation from desired level based on the price sensitivity of the user

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