INTEGRATED CONTROL STRATEGIES FOR DOUBLE SKIN SYSTEMS

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ABSTRACT

This paper represents the next step in the development of occupant responsive optimal control for double-skin systems that was presented at the IBPSA 2003 conference. The presented occupant responsive optimal control (Park et al, 2003b) optimizes in real-time the performance of the facade in terms of energy, daylighting, visual comfort and thermal comfort. In the aforementioned approach, the double-skin façade system was viewed as an 'isolated' system and hence treated as a local control problem, i.e., based purely on information about the state of the façade and its immediate environment. The paper extends the local control problem to a system control problem in which room environmental control and façade control are dealt with simultaneously. It is investigated whether the integrated control significantly outperforms the sub-optimal façade control based on only local state information.

INTRODUCTION

The demand for better performing transparent envelopes has led to the proliferation of double skin systems in the last two decades. They typically contain interstitial louvers and ventilation openings that enforce different airflow regimes through the glass enclosed cavity in summer and winter.

However, the problem with double skin façades is that their operation requires adequate dynamic operation to reach their expected performance (Saelens, 2002). Based on the awareness that only adequate dynamic control of the louver slat angle and airflow regime enables these systems to truly act as active energy savers and indoor environmental controllers, an optimal control strategy for double skin systems was developed and assessed in (Park et al, 2003b). Park's approach uses a lumped model in an embedded real time simulation that feeds a cost function minimization algorithm that finds optimal control variables (louver slat angle, cavity airflow regimes, and the opening ratio of ventilation dampers located at the top and bottom of inner and outer glazing). Additionally, one of the prominent features of the developed control system is that a user in front of a desktop can choose his/her preferred control mode. The following modes were distinguished: energy saving mode, visual comfort mode, thermal comfort mode, autonomous mode, and nighttime mode. But other intermediate modes are also possible as a user can access the web enabled control system settings to set his/her own preferences through any standard web browser. This web interface was developed using the Microsoft .NET web application and LabVIEW 6.1.

A potential problem with the aforementioned approach is that the double-skin façade system is viewed as a 'local' system and hence treated as a local control problem, using only local state information. For this to work, it is assumed that information about the current HVAC operation mode (categorized in three possible states: cooling mode, heating mode, and intermediate mode) can be decided based on the local sensors, i.e. the sensors that measure the immediate environment of the facade. Based on the determined HVAC state the smart controller embedded in the façade system calculates the control variables in real time, minimizing the cost function within a given time horizon. This type of façade controller acts "autonomously" without feedback from the room state, other than knowledge of the HVAC operation state. The benefit of autonomous control is that every façade component can be pre-equipped with its controller and installed on site without the need to integrate its controller in the integrated control systems in the building. But, it is evident that in the de-coupling of the controls of the façade and other building components will lead to sub-optimal control of total building performance.

Hence, this study extends the local control strategy developed in the previous study, to an integrated system control strategy where room state, HVAC operation, and façade control are dealt with at various levels of coupling. Our study investigates whether a locally autonomous façade controller that is not sensitive to the thermal and lighting characteristics of the space behind the façade (such as heat capacity, internal heat generation and others) is able to perform close to optimal.

INTEGRATED SIMULATION MODEL

Simulation models play a major role in the design of the control strategies and systems since the control actions are determined based on the predicted behavior of the system. As briefly mentioned in the previous section, the control system design of double skin systems can be determined in two ways. One is the case (Level I) that the room or the building model is not part of the state space model of the façade control system. This implies that the façade system is treated as a 'local' system and hence results in a local control problem, i.e., based purely on local state information. The benefit of isolating the double-skin façade system is that the resulting façade component with its embedded optimal control can become a part of a building without having to face the integration of its control component in the overall building automation system. If the double-skin façade control intelligence is integrated with a building automation system, its underlying model must contain the set of differential equations for the total system, i.e. for all façade components as well as all other components whose state is affected by the control of the facade, i.e. room air, room enclosure elements (floor, ceiling, and walls), HVAC operation parameters and possibly more. The state space models for all components are solved simultaneously to find the most optimal control actions. These control actions determine louver slat angle, opening ratio of ventilation dampers, and airflow regime at any given moment.

If we assume that the system acts as an autonomous stand-alone system, the optimal control actions are decided based on locally measured data (system state variables and room air temperature) and the underlying model contains only the differential equations of the façade component. In the aforementioned study (Park et al 2003b), this approach (Level I) was chosen to study the potential performance improvements by applying optimal control based on an embedded façade model, assuming autonomous operation.

It is questionable whether the autonomy assumption will lead to adequate control of the façade if embedded in a real building. Even though the control component becomes lightweight and easy to build without the need to integrate it with neighboring room behavior and HVAC control systems, the resulting control actions might be far from optimal. It is the intention of this study to find out how sub-optimal such a control approach will be and to investigate whether this sub-optimality is outweighed by the obvious advantage of the easy installation of autonomous façade control components.

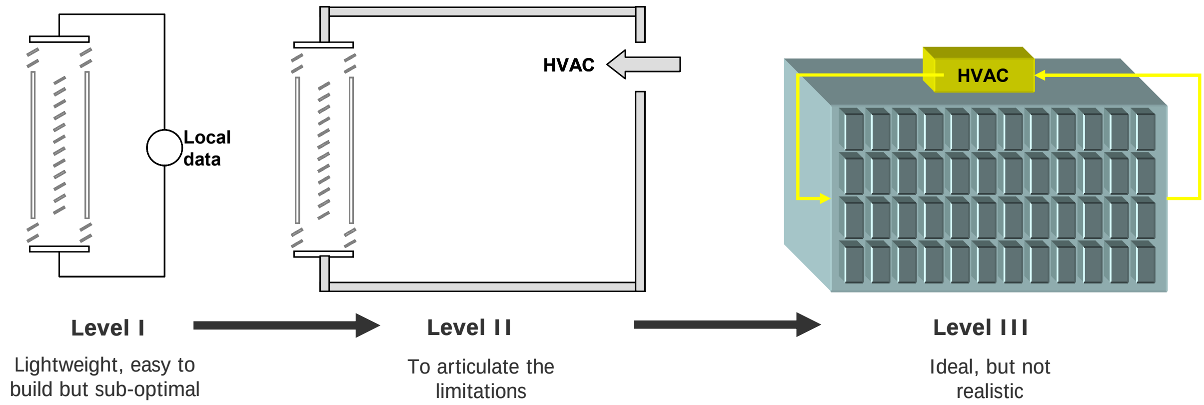


Figure 1. Scope of the control simulation integration

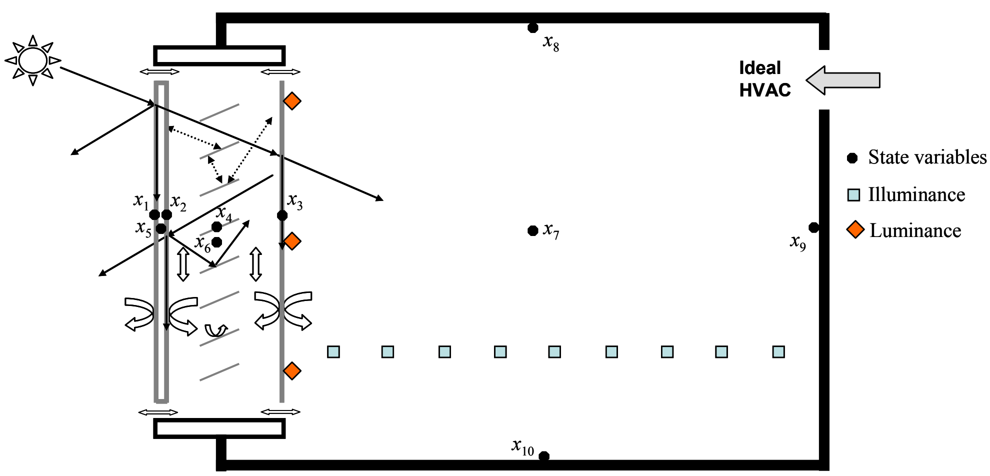


Figure 2. Integrated control on Level II

In this paper, we will only look at the intermediate level of integration (Level II). In the fully integrated case (Level III), the façade control system is fully integrated with the entire building and central HVAC control. Even though Level III is the ultimate objective, we will first deal with the intermediate Level II where the façade control component is integrated with the adjacent room and local HVAC control settings (Fig. 1) but not with the overall HVAC control system on whole building scale. The investigation of Level II will reveal the need to observe the dependency of the façade control on the room characteristics, beyond a control strategy that is based on only shallow knowledge of the adjacent room state (level I).

The remainder of this section will address the development of the integrated control on Level II (Fig. 2). The first step towards this is the development of a façade-room integrated simulation model that drives the Level II control study.

In order to describe the dynamics of double skin systems and the adjacent room and its HVAC system, the inherent complexity of the problem should be recognized. The nature of the dynamics of the systems involves transient convective, conductive and radiative heat transfer and turbulent air flows in a 3D geometry with boundary conditions constituted by outside temperature and solar radiation and wind conditions. In addition, in the integrated control strategies, optimal setting for various components (louver slat angles, ventilation openings) should be determined on a real-time basis to respond to changing weather and desired internal conditions. This calls for a "minimalistic" physical model that can accurately predict the overall states of the systems in real-time without requiring an intensive numerical computation.

Thus, it is intuitively clear that a full-blown 3D model based on actual physical processes and purely physically derived model parameters may in many cases lead to over-engineered models for the stated purposes. Moreover, it is expected that even with the most accurate flow simulations, the complex reality of the cavity airflow, and convective heat exchange processes at glass pane and louver surfaces, is very difficult to model correctly, and some parameters in the underlying detailed models would be hard to "guess" from available empirical studies (ASHRAE [2001a], Clarke [2001], Incropera [1996]).

Rather than taking this approach, a new approach is developed. It is based on the "postulation" of a lumped model, constructed from first principles conservation laws but sprinkled with parameters that are later estimated from experiments. This approach is comparable to a gray box identification technique, described in the general literature on model identification (De Moor [1996], Deque [2000], Tan [2002]).

Hence, in order to describe the dynamics of the double skin system solvable with reasonable efforts, a space-averaged lumped physical model with ten state variables was introduced according to (Fig. 2) (x_1 = outer glazing temperature of the exterior double-pane, x_2 = inner glazing temperature of the exterior double-pane, x_3 = interior glazing temperature, x_4 = louver slat temperature, x_5 = cavity air temperature in the exterior double-pane, x_6 = air temperature in the larger cavity, x_7 = room air temperature, x_8 = ceiling temperature, x_9 = wall temperature, x_{10} = flooring temperature). The state variables in the lumped model represent the space-averaged temperatures in the horizontal and vertical direction. Although this approach does not render explicit information about the vertical and horizontal temperature gradients, it is assumed to be detailed enough to represent the overall thermal characteristics of any double skin system and adjacent room for determining optimal control actions. The model is constructed for one linear meter of façade.

In describing x_1 - x_6, we used the validated '*lumped*' model reported in (Park [2003], Park et al [2004]) without modification and x_7 - x_{10} are then added to the existing model. In the modeling of air movement through the inlet/outlet dampers, 10 possible airflow regimes have been selected (Fig. 3). In Mode #1-2, the interior upper and lower dampers are open (inside circulation) and Mode #3-4 are reversed (outside circulation). For Mode #1-2, air circulating between the room and the cavity is driven by thermal buoyancy while in Mode #3-4, air circulation is driven by thermal buoyancy and wind pressure. Mode #5-8 allow a diagonal airflow either from inside to outside or vice versa. The diagonal airflow is influenced by thermal buoyancy, wind pressure and the pressurization of the mechanical systems. Mode #9 and #10 respectively represent the cases where the four dampers are open/closed. For want of space, the details of the cavity airflow modeling as well as estimating the unknown parameters are not addressed here but can be found in (Park et al [2004]).

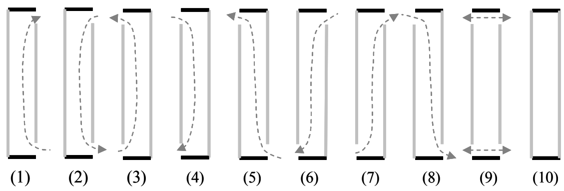


Figure 3 Ten airflow regimes (louver slats not drawn for clarity)

Based on what has been discussed above, the thermal model is expressed in the continuous state space form as shown in Eq. (1).

$$\dot{\mathbf{x}} = \mathbf{A}(u,t)\mathbf{x} + \mathbf{b}(u,t) \quad (1)$$

Where **x** is the system state vector, u is the input vector consisting of control variables and **A** and **b** represent the system state matrix and the load vector that result from the first order energy and mass balance formulation respectively.

Note that the dependency of A on u results in a system that is nonlinear in u. This is prohibitive to a numerical state space solution. By converting the continuous (in time) state space equation (1) to a discrete (in time) state space equation (2), this nonlinearity disappears because $u_k = constant\ for\ t_k \le t \le t_{k+1}$.

$$x((k+1)T) = G(T)x(kT) + H(T) \quad (2)$$

where $G(T) = e^{AT}$, $H(T) = A^{-1}(e^{AT} - I)b$, and T is the sampling time.

Up to this point, the thermal model has been addressed. As the control system will aim for optimal energy saving and optimal use of daylight, an accurate daylight model needs to be added.

The use of daylighting can save energy in two ways: by reducing the usage of indoor electric lighting and by reducing generated heat from electric lights. Thus, the effect of daylighting autonomy with the façade system is determined based on the following assumptions: the perimeter zone is 3m from the interior glazing and an indoor lighting system is integrated with daylighting dimming control. The daylighting dimming control dims the electric lights according to daylighting availability at the point 3m away from the window along the centerline of the room. The reference illuminance can be selected to be any value according to characteristics of the office work.

Another possible lighting control system, although not applied here, would be daylighting on/off control that switches on/off the electric lights based on the photosensor input. In calculating total energy savings by daylight autonomy, the common values for lighting power density, lighting special allowance factor and lighting use factor are obtained from (ASHRAE 2001b).

The daylighting model is not presented here, but discussed in detail in (Park et al, 2003a). The daylighting model is based on pre-simulations with RADIANCE for a typical, rectangular, office space that has a south facing façade. The model can provide indoor daylight distribution such as uniformity, task illuminance and luminance of window surface. Together with the thermal model described in this section, the daylighting model is employed for the integrated optimal control that will be discussed in the following section. It should be noted that the lighting control is based on a typical office space and not on the actual space. It is to be investigated (at level II) how sub-optimal this control is when applied to different actual office configurations.

INTEGRATED OPTIMAL CONTROL STRATEGIES

One of the major problems related to the effective application of the double skin façade in a building is its integration with the different climate systems and their control. The main difficulty is encountered in connecting the functions of the HVAC system with the façade operation (Stec et al, 2005). So far, the realizations of intelligent double skin facades have mostly been limited to the individual control of the façade assuming a separation from other systems. In most cases, such individual control systems have hierarchical control structures based on a set of strategic rules designed for each specific case. One recently reported control strategy that was applied to the Helicon building, a £28 million project in London is quite straightforward (CIBSE, 1996). The fundamental principle of the applied control is a rule-based approach. The rule-based control is "if this, do that" under certain circumstances, and the rules are generally based on expert knowledge. The disadvantage of this approach is that it does not reflect the dynamic behavior of the system, and is only based on the current state information. One of the applied control rules in the Helicon building is that the blinds are lowered to the horizontal position when the solar radiation incident on the façade reaches a threshold (150W/m^2). It is obvious that determining control actions based on predictive simulation may in many instances lead to more intelligent and more optimal control actions than the ones resulting from this rule.

The other approach, as adopted in this study, is to use dynamic embedded simulation to find optimal control actions that minimize a cost function (J) integrated over a certain time horizon. The cost function is constructed by looking at the performance targets of the façade control. The overall performance can be categorized into three elements, which account for three major system utilities: energy use, visual comfort and thermal comfort.

$$J = \int_{t1}^{t2} \begin{bmatrix} r_1(Q_{HVAC}) + r_2(Q_{DA}) + r_3(E_{avg}) \\ +r_4(U) + r_5(L_{avg}) + r_6(\varphi) + r_7(PPD) \end{bmatrix} dt \quad (3)$$

where r_i are the relative weighting factors, Q_{HVAC} is the required heat/cold to keep the room temperature close to the room setpoint temperature, Q_{DA} is the energy savings by daylight autonomy, E_{avg} is the average daylight interior illuminance on the work plane, U is the uniformity, L_{avg} is the average window luminance, φ is the louver slat angle, and *PPD* is the Predicted Percentage Dissatisfied for thermal discomfort (Fanger, 1970). It should be noted that the multiple control scenarios that were mentioned before (energy saving mode, visual comfort mode, thermal comfort mode, autonomous mode) can now be translated in the choice of different weighting factors such that the respective terms in the cost function become heavily weighted and therefore dominate the cost.

Solving for optimal control means determining the optimal control actions that minimize the cost function (J) over a certain period of time as shown in Eq. (4).

$$\begin{aligned} &\min J\left(\varphi,\ AFR,\ OR\right) \\ &s.t.:\ -90° \le \varphi \le 90° \\ &\qquad AFR = 1, 2, 3, 4, 5, 6, 7, 8, 9, 10 \\ &\qquad 0 \le OR \le 100(\%) \end{aligned} \tag{4}$$

where φ is the louver slat angle, *AFR* is the airflow regime mode (Fig. 3), and *OR* is the opening ratio of ventilation dampers. In this study, the function 'FMINCON', one of the MATLAB optimization routines was employed to solve for Eq. (4). The function 'FMINCON' finds a minimum of a constrained nonlinear function of several variables starting at an initial estimate. Inside the function 'FMINCON', the discrete state space and the cost function are described with the sampling time (T) of 15 minute, which is small enough for these slowly time-varying systems. The time horizon is set equal to 6 hour that for Level II simulations seems adequate but needs to be validated.

LOCAL AND INTEGRATED OPTIMAL CONTROL SIMULATIONS

In order to investigate the difference between local (Level I) and integrated (Level II) control strategies, the two types of optimal control simulations were accomplished for two distinct simulation cases under a clear winter day (Atlanta, GA, USA) as shown in Table 1. Case I represents a lightweight (low heat capacity) office space. Case II represents a heavyweight office space.

Table 1 Simulation conditions for Case 1 and 2

	CASE 1 (LIGHTWEIGHT)	**CASE 2 (HEAVYWEIGHT)**
Room	4.5m (D) * 3m (H) * 3m (W)	Same
Ceiling	12 mm acoustic tile	30cm concrete
Inner walls	12mm gypsum + 10cm glass wool + 12mm gypsum	20cm concrete blocks
Slab	10 cm concrete	30 cm concrete
Lighting	13.99 W/m2	Same
Occupant	1	Same
Equipment	10.8 W/m2	Same
HVAC	*Idealized*	Same

The cases are simulated as follows:

- Level I: first, the level I control actions over time are pre-determined from the local control study, as described in (Park et. al., 2003b). The resulting control is then (blindly) applied in the integrated simulation of façade and room.
- Level II: the control actions are determined from the embedded simulation of the integrated façade and room model, where the simulation results for the optimal control emerge from the same model.

The two building cases were chosen as it could be expected that the higher mass of Case 2 may increase the sub-optimality of local control that by default ignores the dynamic characteristics of the room.

Lighting and equipment load densities are assumed to be 13.9W/m^2 and 10.8W/m^2 respectively. 13.9W/m2 corresponds to interior lighting power allowance (ASHRAE, 2001b) and 10.8W/m^2 corresponds to the recommended load factor for medium level office space (ASHRAE, 2001a). In addition, it should be noted that the HVAC system (Fig.2) is *idealized* as follows:

- If x_7 (room air temperature) becomes greater than the room setpoint temperature + 1, then cooling is turned on to keep x_7 equal to the room setpoint temperature (23.5˚C), until there is no cooling load and temperature can float.
- If x_7 becomes smaller than the room setpoint temperature - 1, then heating is turned on to keep x_7 equal to the room setpoint temperature, until there is no heating demand and air temperature can float.
- HVAC operation hours: from 8 a.m. to 6 p.m.

Figure 4(a) shows the calculation of the ten state variables with the outdoor air temperature for Case 1 on Level I. Figure 4(b)-(c) show the room air temperature profile before and after HVAC operation at each sampling time. The green dashed lines represent the setpoint temperature ±1˚C. When the room air becomes greater than 24.5˚C or becomes lower than 22.5˚C, the HVAC kicks in to keep it to be equal to 23.5˚C.

As shown in Figure 4(b), the integrated control (Level II) works better in terms of keeping the room air temperature close to or within the setpoint band (23.5±1.0˚C). This leads to the decrease in the cost function (MJ) in energy saving mode as shown in Figure 4(d) where r_1=r_2=1, and r_3=r_4=r_5= r_6= r_7=0 in Eq. (3), thus calculating total energy consumption by taking HVAC energy consumption and subtracting the energy savings by daylighting autonomy.

The cost function can be regarded as the total energy consumption. As expected, the Level II control is more advantageous compared to the local control (Level I). The details are tabulated in Table 2 and 3. The integrated control (Level II) saves 8.93% and 8.20% more energy compared to local control (Level I). There is a negligible difference in the improvements for a light and heavy room. This means that the expected effect of latency created by more mass in the system was less than expected. In order to make sure that the chosen time horizon was not too small to find the effect of the heavy mass, an additional simulation was conducted with a time horizon of 9 hours. It was found that the results were nearly identical to the results found with six hours, thus ruling out that the time horizon interfered with the conclusion that heavy mass did not add to the sub-optimality of local control.

Table 2 Energy consumption for Case 1 (MJ/day)

TYPE OF CONTROL	Q_HVAC (A)	Q_DA (B)	TOTAL (A-B)
Local (Level I)	3,962.09	0.00	3,962.09
Integrated (Level II)	3,608.23	0.07	3,608.15

$$\left(1-\frac{3{,}608.15}{3{,}962.09}\right)\times 100\% = 8.93\%$$

Table 3 Energy consumption for Case 2 (MJ/day)

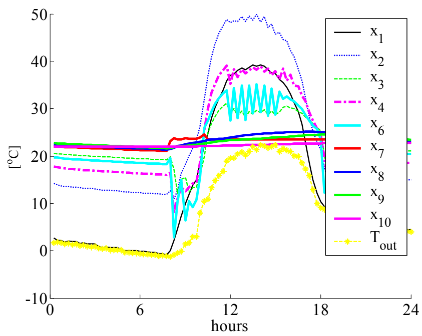
TYPE OF CONTROL	Q_HVAC (A)	Q_DA (B)	TOTAL (A-B)
Local (Level I)	3,152.69	0.01	3,152.69
Integrated (Level II)	2,894.03	0.16	2,893.87

$$\left(1-\frac{2{,}893.87}{3{,}152.69}\right)\times 100\% = 8.20\%$$

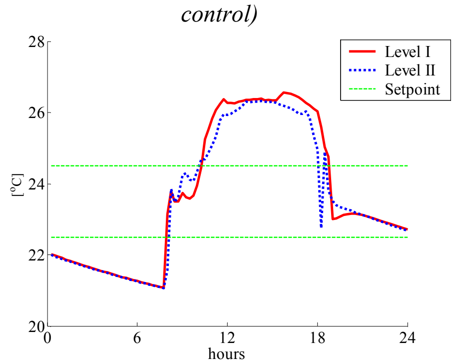
Figure 4(e) shows the air-conditioning operation mode. At nighttime, the HVAC system is in heating mode while during daytime, it is in cooling or intermediate mode all the time. Figure 4(f) shows the louver slat angle (0˚: horizontal, +: towards sky, -: towards ground) with the solar altitude (β) and cutoff angle (ϕ_c). The cutoff angle is the limit angle under which direct solar radiation cannot directly pass between louver blades. At nighttime, the louver slat angle stays at 90˚ such that it can reduce heat loss by longwave radiation between the interior glazing and the colder exterior glazing. A louver slat angle of 90˚ occurs most of the daytime in order to minimize the transmitting solar radiation as well as to decrease interior glazing temperature (x_3 in Figure 2). As shown in Figure 4(g), the local control in intermediate mode allows solar radiation around 8-9 a.m. to the room since it is simply based on the current state information. Comparably, the integrated control can anticipate the room behavior over the next hours within the chosen time horizon (6 hours) so that it blocks solar radiation from the very start to minimize the later cooling need.

As shown in Figure 4(h), at nighttime, Mode #5 airflow regime (refer to Figure 3) occurs so that the exhausted air warms the cold cavity. Mode #5 is useful and can be considered 'a local heat exchanger' as it uses exhaust air to heat up the façade system thus reducing transmission losses. During daytime, the airflow regime is either in Mode #3 and Mode #5 most of the time. Mode #3 utilizes the cold outdoor air to cool the heat-stacked façade cavity to minimize the cooling load (Figure 4(a), (e)). Mode #5 uses the exhaust air to cool the cavity while it warms the cavity at nighttime. The ventilation dampers are open all day in either Mode #3 or #5 and the opening ratio of the dampers are almost 100% as shown in Fig. 4(g), which means maximizing the beneficial use of the cavity airflow.

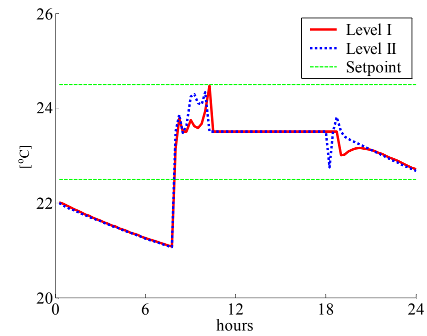
Figure 4(k) shows the daylighting performance in energy saving mode. The average daylighting illuminance is far under the threshold values (between 500 and 3340 Lx). It can be inferred that during daytime, the cooling load reduction by blocking the solar radiation is more beneficial than the energy savings through daylighting autonomy. Around sunrise time when the solar radiation is comparably weak and the air conditioning mode is intermediate, the Level I control allows sunlight (Figure 4(e), (f), (g)) while Level II allows only skylight (Figure 4(e), (f), (g), (k)).



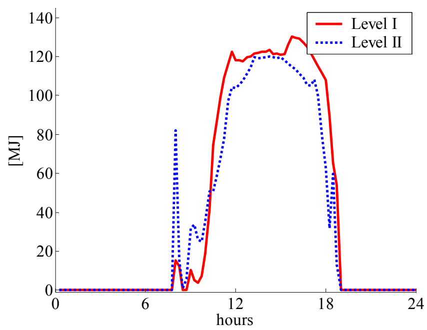
(a) State variable and outdoor air temperature (Level I control)



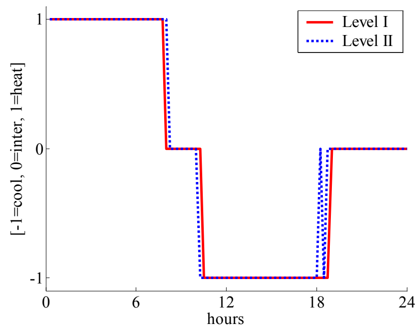
(b) Room air temperature profile (before HVAC's operation at each sampling time)



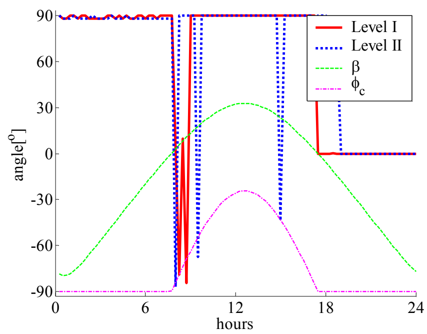
(c) Room air temperature profile (after HVAC's operation at each sampling time)



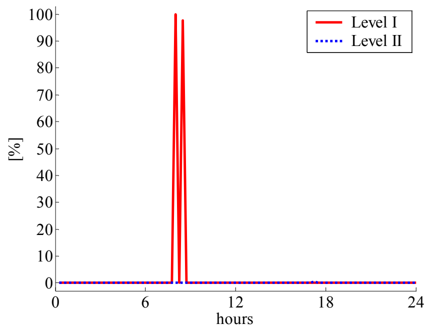
(d) Cost function (energy saving mode)



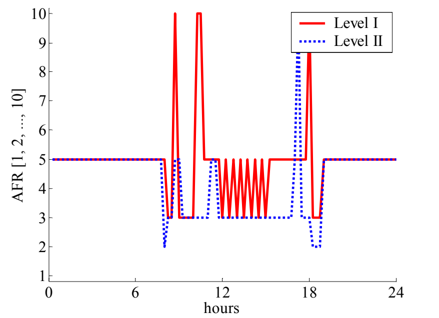
(e) Air-conditioning operation mode



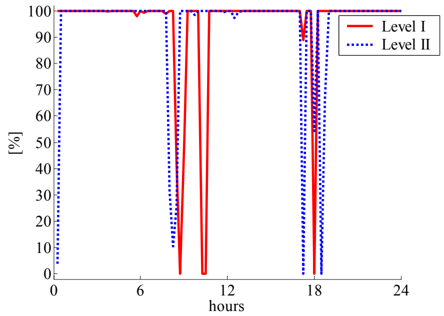
(f) Optimal louver slat angle



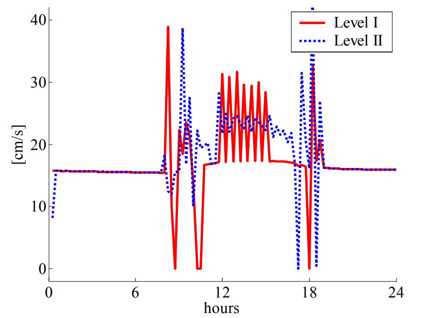
(g) Permeability



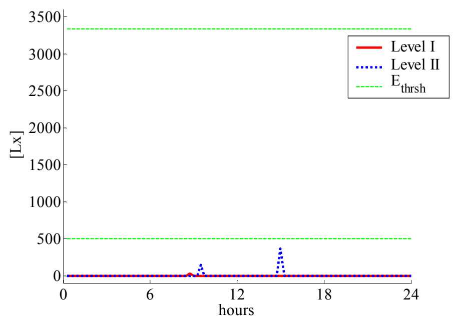
(h) Airflow regime



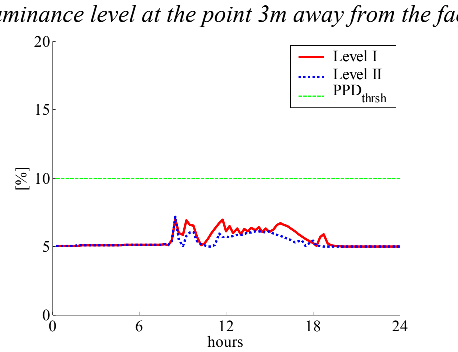
(i) Opening ratio of dampers



(j) Cavity air velocity



(k) Illuminance level at the point 3m away from the façade



(l) PPD

Figure 4 Simulation results with local (Level I) and integrated control (Level II) for Case 1 under a clear winter day

It is interesting that the maximum interior glazing temperature is low (31.18˚C for Level I, 28.9˚C for Level II) compared to general window systems because the cavity air flows during most hours of the daytime. Consequently, the values of PPD in both cases are in the comfortable range. The maximum PPD is 7.06% and 7.16%, respectively (Figure 4(l)).

The control simulations for Case 2 are quite similar to Case 1, and omitted in this paper. Note that the energy consumption in Table 2 and 3 is valid only for the cases considered, i.e. both south-facing facades. The relative energy saving effect of Level II control might increase for East and West facing facades. Although this effect is expected to be relatively minor, this needs to be verified in follow-up studies.

DISCUSSION AND FUTURE WORK

The effect of two different control strategies was studied on the energy, lighting and thermal comfort conditions in a room behind an intelligent double skin facade. Both a local "autonomous" and an integrated control of the façade system were simulated to find out how much the different control actions will influence the desired room conditions. This was done for two room types, one light mass and the other heavy mass, for a typical winter day in the Atlanta climate. It was found that the locally generated control leads (as expected) to sub-optimality, albeit of moderate proportions. Although there are clear instances during the day that the local control generates the wrong behavior, the periods that this occurs are fairly short.

Although this seems to indicate that autonomous control is "good enough", more study is necessary. It should be recognized that some of the flow regimes of the façade can only be realized in harmony with the HVAC system operation mode. If these flow regimes are deemed important, then autonomous control is not an option as this type of control is not connected with the HVAC control system.

The current phase of this ongoing research is dealing with Level III integrated control on whole building level, and the techno-economical optimal configurations of double-skin facades and their control systems.

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