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COMPARATIVE STUDY OF STATIC VS. DYNAMIC CONTROLS OF DOUBLE-SKIN SYSTEMS

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ABSTRACT

This study compares three different control strategies for double-skin systems. The analyzed control strategies are (1) rule-based approach, (2) exhaustive search and (3) gradient-based search. The fundamental principle of the rule-based approach 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 transient behaviour of the system. The exhaustive search, so called "brute force" search, tests all possibilities for the solution while the gradient method uses the derivative of the cost function.

This study aims to investigate differences in the performance of the systems operating under various control strategies. The control simulation uses the lumped calibrated model developed in (Park et al., 2003a) and optimization algorithms to solve for optimal control variables to minimize a cost function over the time horizon.

It was found that the rule-based approach works significantly worse in terms of decreasing the cost function in both heating and cooling modes. There is a negligible difference between the gradient and exhaustive methods. Considering significant computation time required for the exhaustive method, the gradient method is suited for optimal control for a double skin system.

INTRODUCTION

Glass curtain-walls have been applied in buildings because of the architectural aesthetics, allowance for daylight, visual contact with outside and a feeling of openness. However, they may cause excessive undesired heat gain (loss), asymmetric thermal discomfort, glare due to an over-lit glazing surface, etc. To reduce the aforementioned problems, double-skin façade systems have been introduced (Oesterle et al., 2002; Wigginton et al., 2002). They typically contain interstitial louvers and ventilation openings that enforce different airflow regimes through the glass enclosed cavity in summer and winter.

The current problem with the double-skin systems is that the operation of control variables (louver slat angle, opening ratio of ventilation damper and airflow regime in the cavity) is not based on optimal control theory which accounts for 'dynamic characteristics of the systems' but uses a rule-based approach (Saelens, 2002). Dynamic characteristics refer to a system's dynamic response in reaction to input received by the system.

Figure 1 illustrates the dynamic characteristics of the system. In the case of a hot-air balloon system operated by the buoyancy of heated air, the input variable (control variable) is the amount of heat supplied to the system and the output variable (state variable) is height, velocity and accelerated velocity of a hot-air balloon. 'Dynamic characteristics' is based on a system model that describes output variables according to system input. Therefore, it can control the state variable (height) by adjusting the input variable (amount of hot air transferred to the balloon) before the hot-air balloon attained the objective point (height). Static control does not use the dynamics of the system and make a decision based on the output variables, thus leading to overshooting (Figure 1). However, in the real operation of a hot-air balloon, serious overshooting does not occur, because an operator controls the hot-air balloon using heuristics along with the operator's trained and empirical intuition. Similarly, a driver typically does not know the system model that describes the dynamic characteristics of a car but stoppage that drastically goes beyond a stop line does not occur often, usually because he/she controls the car using trained empirical intuition.

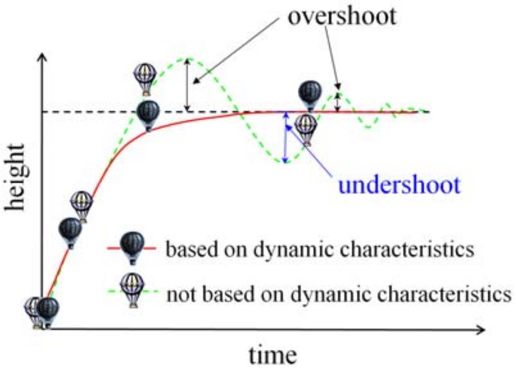


Figure 1 Example of static and dynamic controls

The rule-based control, as an example of static control, determines the rule based on the 'intuition' or ‘experience’ of control designer (if this, do that). Accordingly, the performance of the system is determined by ‘how well rules are made’. As an example of dynamic control, we give an optimal control. An optimal control determines the values of the control variables that minimize the cost function over a given time.

Such dynamic controls can be solved analytically or numerically. Analytical methods include: Pontryagin’s minimum principle, Hamilton-Jacobi-Bellman equation, Riccati equation according to a type of problems (discrete vs. continuous, linear vs. nonlinear, free final state vs. fixed final state, open-loop vs. closed-loop) (Lewis, 1995). These methods can be applied if the system is simple and has no disturbances, but if the system is nonlinear (like a double-skin system) and control variables are readily changeable due to the occupant’s intervention, it is difficult to apply an analytical method.

The numerical methods can be classified as follows:

- Gradient method: this method finds the optimal variables that minimize the cost function, using the gradient (the partial derivatives of the cost function). This method applies only when the cost function is differentiable, and is defective in that it sometimes converges to a local minimum, but it can find the optimal control variables quickly.
- Exhaustive search method: This method investigates all possible cases and selects the best one (optimal control variables). This method does not need the initial guess as required for the gradient method and is applicable when the cost function is discontinuous. However, it has the disadvantages that it is computationally expensive when the number of cases is large.
- Genetic algorithm: This optimization method proceeds by applying genetic laws. It is fundamentally different from the gradient method, which finds optimal value using the gradient of the cost function. It can apply to various types of the optimal problem regardless of the differentiability of the cost function. However, the disadvantage is that it may be time-intensive, depending on the number of individuals.
- Simulated annealing: The inspiration of this method is annealing in metallurgy, and it is usually applied to global optimization problems in a large search space. At each iteration, it selects the optimal solution by replacing the current solution with a random ‘nearby’ solution. To compensate for the weakness of converging to local minima, ‘uphill’ movement is tolerated in the search process. The key advantage of this method is that it can apply various types of optimal problems and converges nearby the global minimum. However, to obtain a good solution, a large calculation time is needed.

The objective of this paper is to find a control strategy appropriate to optimizing the operation of the double skin system in real time. It compares the performance of the various control strategies and identifies the most effective. Control strategies selected for comparison are (1) rule-based control, (2) gradient method, and (3) exhaustive search method. (1) is an example of a static control not based on dynamic characteristics, and (2), and (3) are examples of dynamic control. Genetic algorithms and simulated annealing are excluded in this study, because these methods are usually computationally intensive, and so they may be inappropriate for real-time optimal control of the double-skin system.

CONTROL STRATEGIES

Rule-based control

Rule-based control depends on the rules that are determined by ‘intuition’ or ‘experience’ and an example is the Helicon building (CIBSE, 1996) (Figure 2).

Figure 2 The Helicon building

The control strategy applied to the Helicon building is as follows: 1) When the solar radiation incidents on the façade reaches a threshold (150W/m^2), the blinds are lowered to minimize solar gain. 2) When space temperatures subsequently fall, zone control, on a floor-to-floor basis, reverts to maximizing daylight, and the tilt angle of the blinds reduces. 3) The ventilation is triggered when the cavity air temperature reaches 28℃ and higher (CIBSE, 1996). In the paper, the applied rule-based control was used without modification except that the opening ratio of the ventilation dampers are assumed to be controlled in only two positions: 0%(closed) and 100%(fully open) since it is not clearly described in the literature (CIBSE, 1996).

Gradient method

The dynamic control is achieved in three steps: (1) develop the mathematical model of the system (Equation (1)), (2) define a cost function (J) to quantitatively evaluate the system's performance (Equation (2)), (3) determine the optimal control variables that minimize the cost function over the given time horizon.

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

$$\min \boldsymbol{J} = \int_0^{\boldsymbol{t}} \boldsymbol{L}(\boldsymbol{x}(\boldsymbol{t}),\boldsymbol{u}(\boldsymbol{t}),\boldsymbol{t})\boldsymbol{dt} \qquad (2)$$

Exhaustive search method

The exhaustive search method evaluates the cost function for all possible cases as shown in Figure 3. This method is sometimes called 'brute force'. It is highly probable to find the nearly global minimum, because this method examines all possible combinations of control variables. However, if the optimization problem involves continuous variables, it is mandatory to convert to discrete variables, and in general, the number of possible solutions increases exponentially. This method is straightforward because the solution process of the optimization problem (Equation (2)) is not required.

In this study, the louver slat angle is operated at 10˚ intervals, and the ventilation damper opening rate is assumed to operate in only two positions, 0%(fully closed) and 100%(fully open). Consequentially, we accomplish this study by assessing the cost function of 136 cases and finding the optimal values of the control variables (Figure 3).

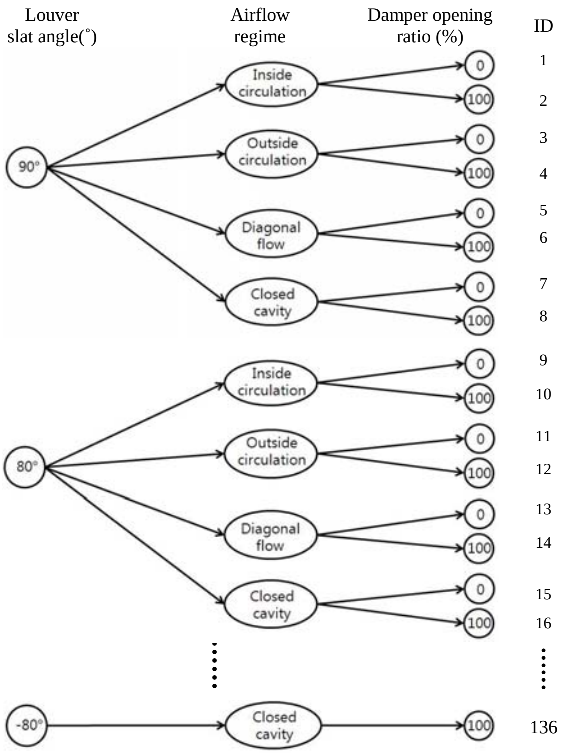


Figure 3 Exhaustive search tree

SIMULATION MODEL

The state space model that explains the system's dynamic characteristics was developed in a previous study (Park et al, 2003a). The model is comprised of a thermal and an airflow model. The thermal model reflects long wave radiation, short wave radiation, and convective heat transfer, and ten possible airflow regimes have been selected in the airflow model as shown in Figure 4. The details of the system's physical configuration are as shown in Figure 5.

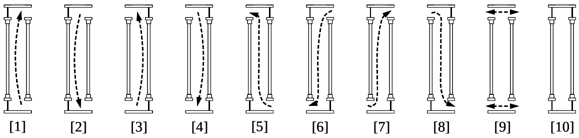


Figure 4 Ten airflow regimes
(louver slats not drawn for clarity)

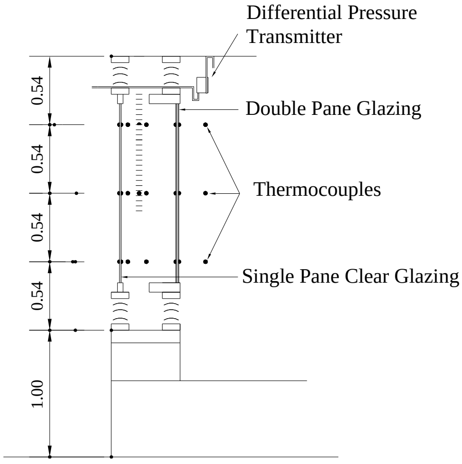


Figure 5 Test facility

It should be noted that the room or the building model is not part of the state space model, which means that the double-skin system is treated as a 'local system' and hence a local control problem, i.e., based purely on local state information. The benefit of isolating the smart double-skin facade system is that the resulting facade component with its embedded optimal control can become a part of and building model. If the double-skin facade system needs to be incorporated into a room or a building model, a set of differential equations for other states such as floor, ceiling, and walls can be added to Equation (1) for a simultaneous solution.

OPTIMAL CONTROL VARIABLES

The overall performance of the double-skin system is measured by three major system utilities: energy saving, visual comfort and thermal comfort. The cost elements in energy utility include convective and radiative heat loss (gain), transmitted solar radiation, beneficial use of the cavity airflow regime and daylighting autonomy. The cost elements in visual comfort include average daylight illuminance, uniformity, average luminance of the interior window surface and outward visibility through the slats. The thermal comfort is expressed in predicted mean vote (PMV). Each utility consisting of its sub-elements can be formulated in the cost function (*J*) as follows:

$$J=\int_{t_1}^{t_2}\begin{pmatrix} r_1(Q_{cv,rd}+Q_{sol,trans}+Q_{air}+Q_{DA}) \\ +r_2 pf_1(E_{avg})+r_3 pf_2(U)+r_4 pf_3(L_{avg}) \\ +r_5 pf_4(\phi)+r_6(PMV)^2 \end{pmatrix} dt \tag{3}$$

The details of the cost elements are discussed in Park et al (2003a; 2003b). For want of space, only the cost elements relevant to energy use are dealt with in the paper for the sake of easy comparison. Thus, the const function (Equation (3)) can be simplified as Equations (4)-(5).

$$J_{heat}=-\int_{t_1}^{t_2}(Q_{cv,rd}+Q_{sol,trans}+Q_{air}+Q_{DA})dt \tag{4}$$

$$J_{cool}=\int_{t_1}^{t_2}(Q_{cv,rd}+Q_{sol,trans}+Q_{air}-Q_{DA})dt \tag{5}$$

The optimal control problem is formulated as shown in Equation (6).

$$\begin{aligned} &\min J(\phi, AFR, OR) \\ &s.t. -90^\circ \le \phi \le 90^\circ \\ &\quad AFR = 1,2,3,4,5,6,7,8,9,10 \\ &\quad 0 \le OR \le 100\,(\%) \end{aligned} \tag{6}$$

Due to the nonlinearity of the dynamics of the system and the constraints on the control variables, it is difficult to find the analytical solution. Additionally, the optimality problem involving continuous control variables (ϕ, *OR*) and discrete control variables (*AFR*, Figure 4) leads to a combinatorial problem, which is unrealistic to solve (Winston, 1994). The discrete airflow regime (*AFR*) is thus translated as a continuous variable (*AFR**). When *n≤AFR*≤n+1*, the *AFR* is defined as *n* and the opening ratio (*OR*) is determined as shown in Figure 6.

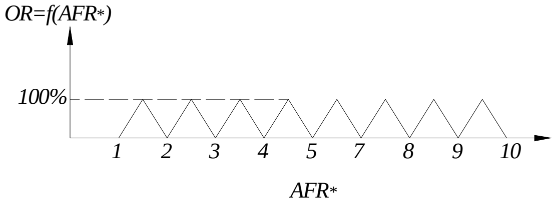


Figure 6 Converting discrete variable (AFR) to continuous variable (AFR)*

To deal with the problem numerically, the function 'FINCON', a MATLAB optimization routine, is employed. The function 'FMINCON' finds the minimum of a constrained nonlinear function of several variables starting at an initial estimate. Inside the function 'FMINCON' the mathematical model and the cost function are described with the sampling time (T) of 15 minutes which is small enough for these slowly time-varying systems. The function 'FMINCON' searches for optimal control variables in the iterative process as shown in Figure 7.

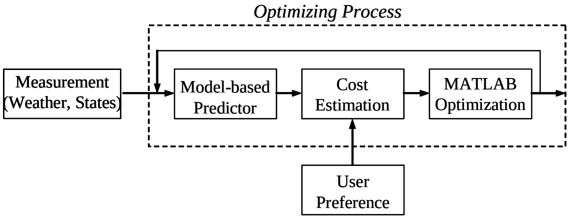


Figure 7 Iterative process to solve for optimal control variables

Note that the rule-based control is not necessarily given by the model and the cost function. Instead, the rule should be established using the 'intuition' or 'experience' of the control designer. Therefore, the rule-based control method does not require an iteration as shown in Figure 7. The exhaustive search method finds the optimal control variables by searching all possible cases. So, the cost functions formulated in Equations (4)-(5) are necessary, but numerical iteration (Figure 7) is not applied.

In the rule-based and exhaustive search methods, the opening ratio (*OR*) of ventilation dampers is considered to have two positions, 100% (fully open) and 0% (fully closed) under the assumption that the cavity air is fully utilized as long as cavity air can contribute to reduction of cooling (heating) energy.

OPTIMAL CONTROL SIMULATION

The optimal control simulation was accomplished for both winter and summer days under a clear sky. Figure 8 shows the simulation results for the winter day (heating mode, Equation (4)). Figure 8(a) shows the optimal control variables of the rule-based control. There are large differences in the louver slat angle and the opening ratios of ventilation dampers between Figures 8(a) and 8(b)-(d). The cost function elements for the three control methods are shown in Figure 9.

In the exhaustive search (Figure 8(b), (c)) and gradient methods (Figure 8(d)), the optimal louver slat angle keeps track of the solar altitude so that it can absorb direct solar radiation during the daytime to reduce the heating load. It can be inferred that the dynamic control which considers the dynamic characteristics of a room is more effective than the rule-based control that determines the louver slat angle using the outside daylight condition. The airflow regime is similar between the exhaustive search and the gradient method. The airflow regime during nighttime is the diagonal airflow mode (Figure 4 [5]). In that mode, the exhausted air warms the cold cavity to heat the facade system and thus reduce transmission losses. In daytime, internal circulation (Figure 4 [1]) occurs so that the hot cavity air circulates into a room space for the reduction of the heating load. The closed cavity airflow regime occurs (Figure 4 [10]) directly after sunrise, because it makes the cavity air temperature higher than the indoor setpoint temperature (23.5℃). The optimal opening ratio (*OR*) of the exhaustive search and gradient method remains near 100% (fully open), except in the closed cavity regime (Figure 4 [10]). This shows that the aforementioned assumption about 100% opening ratio in the exhaustive search method is reasonable.

The rule-based control closes the ventilation dampers under the heating mode to trap the heated air in the cavity, thus increasing the interior glazing temperature. This makes $Q_{cv,rd}$ greater than those in the exhaustive search and gradient methods (Figure 9(a)). But, overall performance of the rule-based control is the worst (Figure 9(a)), because this method can't take into account the cost function (Equations (4) and (5)) which specifies the overall performance ($Q_{cv,rd}$+ $Q_{sol,trans}$ + Q_{air} + Q_{DA}).

In the cooling mode, the exhaustive search and gradient methods perform better than the rule-based method. This happens because $Q_{cv,rd}$ is reduced as much as possible using the beneficial airflow regime (Figure 4, mode [5]) and the daylighting autonomy.

In the cooling and heating modes, the exhaustive search method is more favourable, but, there is little difference compared to the gradient method (Fig. 9). The calculated optimal control variables are nearly identical for the exhaustive and gradient methods as shown in Figure 8. However, the results of the rule-based control are different from the other methods.

In the exhaustive search method, the simulation runs were executed by changing the operational intervals of the louver slat angle (5˚, 10˚) to investigate the impact of it on energy and daylighting performance.

It was found that there is no significant difference between two (5˚ interval, 10˚ interval). The first reason for this is that the solar radiation is significantly reduced when passing through the three layers of the glazing (exterior clear glazing + interior double glazing [6mm low-e + 12mm air + 6mm clear] (Figure 5). For example, if the transmittance of each glazing is 20%, then the radiation that reaches the indoor is 0.008 (0.2Ｘ0.2Ｘ0.2), or 0.8%. The second reason is that the variation in the permeability according to the operation interval of the louver slat angle is not significant (Figure 10). 'permeability' is defined as the ratio between the unshaded area and the total area between the slats (Pfrommer, 1996).

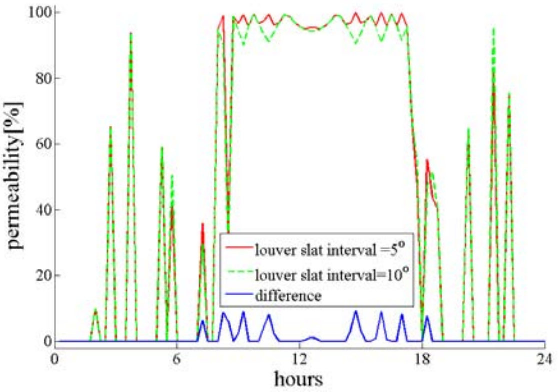


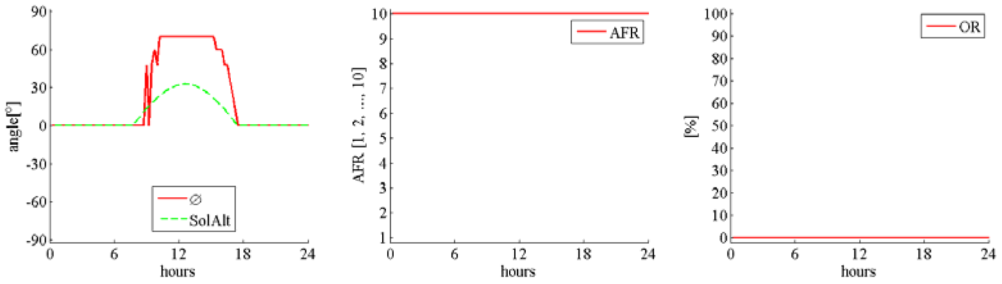
Figure 10 Permeability

In Figure 9, the exhaustive search method is better than the gradient method but the difference is negligible. The gradient method uses a continuous louver slat angle and a damper opening ratio (Figure 8); on the other hand, the exhaustive search method operated with a discrete louver angle (5˚ and 10˚) and two-position damper opening ratio (0 or 100%). However, the result is contradictory. It is speculated that this is because the solution of the gradient control converges to a local minimum instead of a global minimum, as explained in the section above.

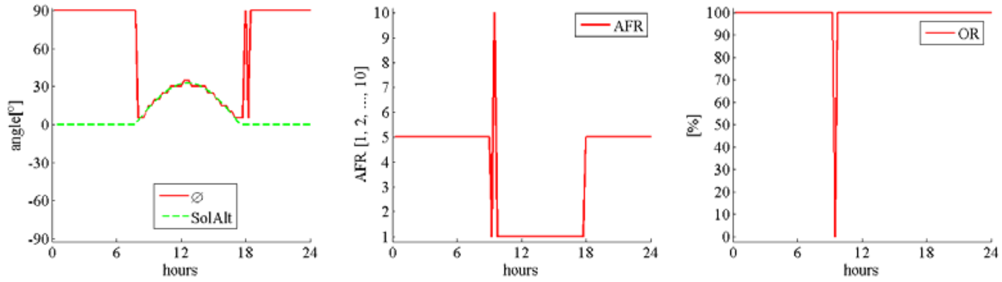
For optimal control of the double-skin system, it is important to select the appropriate time horizon. If the time horizon is large, the thermal inertia of the system is sufficiently accounted for, but if it is too large, it is difficult to apply it to real-time optimal control, because of the long computation time to solve the optimization problem expressed in Equation (6). In the paper, optimal control simulation runs were performed with the time horizon of 15 minutes, 1 hour and 3 hours and the results are shown in Table 1.

Table 1
The cost function and computation time

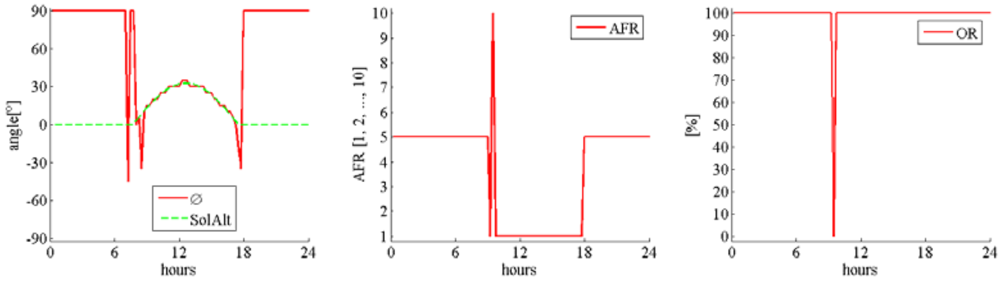
TIME HORIZON	**CONTROL STRATEGY**	**COST FUNCTION (MJ/DAY)**		**COMPUTATION TIME**
		Heating mode	Cooling mode	
15 minutes	Gradient	-29.12	-0.56	1.9 sec.
	Exhaustive search (10°)	-28.86	-0.91	0.7 sec.
	Exhaustive search (5°)	-29.13	-2.06	1.9 sec.
1 hour	Gradient	-24.69	0.86	36.3 sec.
	Exhaustive search (10°)	-24.21	-0.97	6 min. 30 sec.
	Exhaustive search (5°)	-29.40	-2.17	9 min. 15 sec.
3 hours	Gradient	-29.66	-0.61	4 min. 23 sec.
	Exhaustive search (10°)	-	-	-
	Exhaustive search (5°)	-	-	-



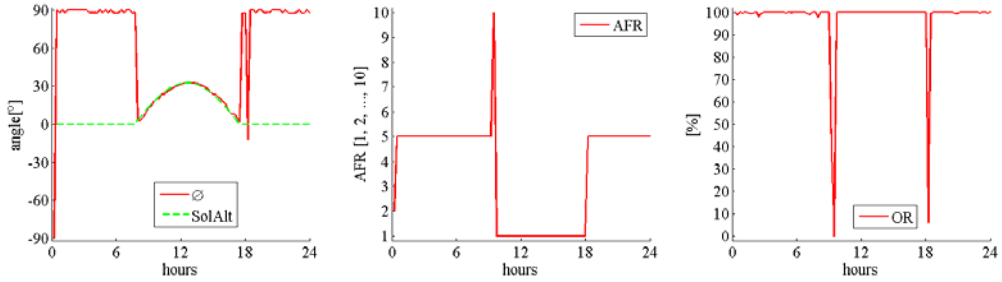
(a) Rule-based method



(b) Exhaustive search method (intervals of louver slat angle = 10°)

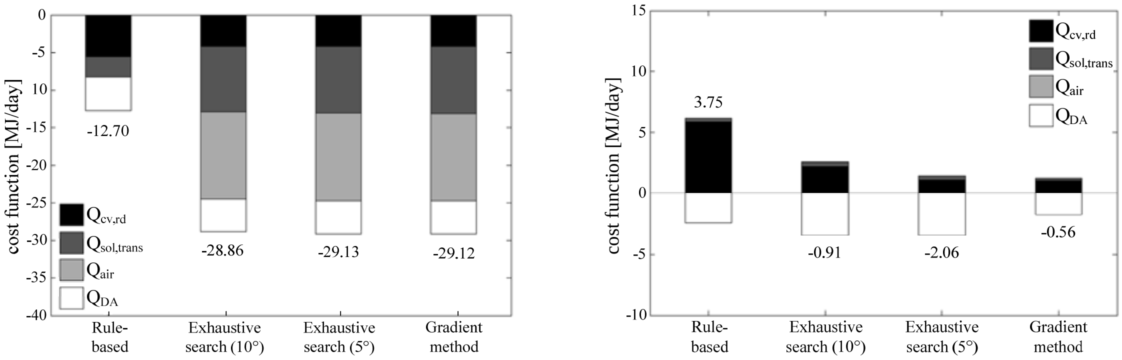


(c) Exhaustive search method (intervals of louver slat angle = 5°)



(d) Gradient method

Figure 8 Control variables (in heating mode, sampling time = 15 min, ϕ =louver slat angle, SolAlt = solar altitude, AFR = Air Flow Regime [Figure 4], OR = Opening ratio of ventilation dampers)



(a) Heating mode (winter)

(b) Cooling mode (summer)

Figure 9 Comparison of cost elements (the number indicates the sum of cost functions; the less, the better)

The cost function of the gradient method increases when time horizon increases from 15 minutes to 1 hour. It is speculated that the solution converges to a local minimum but the difference is not significant. In the exhaustive search method, as the time horizon increases, the computation time increases exponentially. So, the results are not obtained for the time horizon of 3 hours. It can be concluded that the time horizon of 15 minutes is good enough to take into account the dynamics of the double skin systems.

The energy saving potentials of three control strategies are investigated (time horizon: 15minutes) as shown in Table 2. The assumptions are as follows: (1) heating and cooling equipments operate from 8 A.M. to 6 P.M. (2) The overall heating equipment efficiency is 90%. (3) The COP of cooling equipment is 1.1 since an absorption chiller is popular in South Korea. It should be noted that the results in Table 2 is not a comparison between a common double glazing and the double-skin system but a comparison between three control strategies. The energy cost reduction (A-B) in Table 2 is the case of a very small double-skin unit (glazing area= 3.17m^2) based on the test facility (Figure 5). The potentials will be greater as the glazing area increases. In addition, the proper control will contribute to downsizing of HVAC and heat distribution systems.

Table 2
Comparison of the energy saving potentials (won/day)

	RULE-BASED (A)	**GRADIENT METHOD (B)**	**COST REDUCTION (A-B)**
Heating mode	-1,220	-2,538	1,318
Cooling mode	325	42	283

* glazing area: 3.17m^2, energy price (won/kWh): http://www.kdhc.co.kr/

CONCLUSION AND FURTURE WORK

In the paper, three applicable control strategies (rule-based, exhaustive search and gradient method) are selected for comparison. The lumped simulation model of the double-skin system developed in (Park et al, 2003a) is utilized, and the optimal control simulation is performed. For the gradient method, a MATLAB optimization routine, FMINCON, was used to determine optimal control variables.

Through the comparison of three control strategies, it was shown that the exhaustive search and gradient methods perform better than the rule-based method, and that the difference between the exhaustive search and the gradient method is negligible. In addition, the exhaustive search and gradient methods with a time horizon of 15 minutes are similar in terms of the cost function and computation time. In the gradient method, the cost function decreases and computation time increases as the time horizon increases. As the time horizon increases from 1 hour to 3 hours, , the computation time increases drastically but the cost function scarcely change. In the exhaustive search method, the computation time increases exponentially as the time horizon increases. These results show that a time horizon of less than 1 hour is suitable for the real-time optimal control of a double-skin system. Also, even if the operation interval of the louver slat angle is changed (from 10˚ to 5˚), the overall performance of the system does not change much in the exhaustive search method. Most of previous studies on double-skin systems (Saelens, 2002; Ballestini et al, 2005; Ding et al, 2005; Gratia and Herde, 2004a, 2004b, 2007a, 2007b; Hamza, 2008; Høseggen et al, 2008; Saelens et al, 2008; Pappas and Zhai, 2008) report performance using the rule-based method. If previous studies are re-evaluated using the exhaustive search or the gradient method proposed in the paper, better performances of the system will be expected. The control strategies applied in this paper can be applied to various building systems (boiler, chiller, cooling tower, shading system, etc.). The following studies are ongoing; (1) thermal comfort and visual comfort assessment. (2) Analysis of the impact of the double-skin system on the whole building integrating the control strategies of whole building simulation tools (e.g., Energy plus, esp-r, etc.).

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NOMENCLATURE

x	state vector
A	state matrix
b	load vector
u	control or input variables
L	integrand of cost function
t	time
r_i	relative weighting factors
$Q_{cv,rd}$	heat gain in the room space by convection and radiation on the interior glazing
$Q_{sol,trans}$	sum of transmitted direct and diffuse solar radiation
Q_{air}	heat gain the room space by beneficial airflow regime from the cavity to the room space or outside
Q_{DA}	energy savings by daylighting autonomy
pf_i	square penalty function
E_{avg}	average daylight interior illuminance on the work plane
U	uniformity
L_{avg}	average window luminance
ϕ	louver slat angle (0˚: horizontal, (0˚~90˚: towards the sky, -80˚~0˚: towards the ground)
J_{heat}	cost function in heating mode
J_{cool}	cost function in cooling mode
AFR	AirFlow Regime (Figure 4)
OR	opening ratio of ventilation damper