COMPARISON OF DIFFERENT OPTIMAL CONTROL STRATEGIES OF A DOUBLE-SKIN FACADE

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ABSTRACT

This study presents optimal control strategies of the system using a Generalized Pattern Search and Genetic Algorithm. Then, the aforementioned two approaches are compared to three other optimal control strategies of a double skin façade reported in the literature. To compare control strategies, the lumped simulation model developed in the previous study (Yoon et al, 2009) is integrated into MATLAB optimization routines (patternsearch, ga) which determine optimal control variables (blind slat angle, airflow regime, and opening ratio of the ventilation dampers). It was found that the optimal control based on the Genetic Algorithm performs better than the others, but takes longer to search for converging solution sets.

INTRODUCTION

Recently, a glazed façade system of non-residential buildings achieved wide recognition as an important component of buildings for those concerned with the depletion of fossil fuels, global warming, and greenhouse gases, as well as the improvement of thermal comfort and Indoor Environment Quality (IEQ). In other words, a dynamic control system must be required to predict and control various performance aspects (energy savings, thermal comfort, and visual comfort) inherited in the glazed façade system (Gratia & Herde, 2004; Park, 2003; Saelens, 2002; Yoon et al, 2009).

The Double-skin Façade consists of exterior/interior glazing, a cavity space, a blind, and a ventilation damper. This setup is more expensive than other glazed façade systems, but is catching on as an environmentally-friendly glazing technique to acquire the aforementioned performance. The Double-skin Façade system must be equipped with an appropriate dynamic optimal control. In particular, optimal control of the Double-skin Façade that predict and optimize physical transport processes is not easily achievable due to highly nonlinear dynamic characteristics of the system. But it is obvious fact that optimal control strategies are positively necessary for the performance improvement of a whole building.

General control of the Double-skin Façade system is mostly on a rule-based approach that has no consideration for dynamic characteristics. As the rule-based approach was controlled by the pre-defined rules or conditions based on the intuition and experience of control designers, its control performance is inferior to dynamic controls over a given time horizon (Saelens, 2002; Yoon et al, 2009). A previous study (Yoon et al, 2009) classifies three control strategies (rule-based approach, exhaustive search, and gradient-based search) integrated with a lumped simulation model, and compares control variables (blind slat angle, airflow regimes, and opening ratio of the ventilation dampers) and cost function (energy use) of both heating and cooling modes. In the result, the exhaustive search and gradient-based search using numerical optimization approach shows more remarkable control performance than the rule-based approach.

This study will propose other optimal control techniques using the direct search method Generalized Pattern Search (GPS) and the heuristic Genetic Algorithm (GA) method. The primary objective of this study will search for suitable optimal control methods among a rule-based approach and various optimization techniques (exhaustive search and gradient-based search, GPS, and GA). For this study, the lumped mathematical model (airflow model + thermal model) used in the previous study (Yoon et al, 2009) had proven to give enough accurate results. The lumped simulation model was used in the iterative process of optimization algorithms in the MATLAB platform. The simulation performed to determine the optimal control variables when a time horizon increases at an interval of 15 minutes over the one day in the summer and winter.

OPTIMIZATION METHOD

The optimal control of the Double-skin Façade needs to account for dynamic characteristics of the system followed in a complex physical environment. The dynamic optimal control can acquire significant performance results (energy use, daylight, and thermal comfort) through direct modulation of control variables in real time. Unlike optimal control, the rule-based approach does not account for dynamic characteristics of and is based on the present state of the state variables. For example, the rule-based approach of the Double-skin Façade is to keep controlling blind slat angle or airflow regimes according to solar radiation and cavity air temperature measured at the time (CIBSE, 1996). The abovementioned control strategies can be divided into academic (optimal control) and practical (rule-based) approaches.

The GPS approach, which was proposed in Box (1957), Hooke & Jeeves (1961), is one of the direct search methods. In particular, it was extensively used for optimization problems due to easy application and realization (Lewis et al, 1998). The previous study (Hooke & Jeeves, 1961; Torczon, 1997; Lewis et al, 1998; Polak & Wetter, 2003; Wetter & Polak, 2003) describes the GPS method in detail. It calculates optimal variables from the current state (x_k) to the following state (x_{k+1}) by using Equation (1).

$$x_{k+1} = x_k + \Delta_k d_i, \quad i \in (1,...,n) \tag{1}$$

where Δ_k is mesh size factors ($\Delta_k > 0$), d_i is the set of directions ($d_i = s^i \times e_i$) which are composed of standard unit basis vectors ($e_i, \quad i = 1,...,n$) and fixed parameter ($s \in R^n$) to reflect many design variables. In other words, the GPS method searches the optimal cost function to satisfy $f(x_i) < f(x_k)$.

Unlike a gradient-based approach that needs first-order and second-order derivatives of the cost function, the GPS approach efficiently finds global minima discontinuous and non-differential problems, and requires less computation time than heuristic methods (simulated annealing, genetic algorithm, and Tabu search). However, it has a disadvantage to converge local minima when a cost function is strongly nonlinear (Dolan et al, 2003).

The GA that was developed by Holland (1975) is a random search technique inspired by the principles of natural evolution. To evolve toward better solutions, it is necessary to utilize optimization techniques such as selection, crossover, and mutation to generate fittest individuals from the population which is encoded into binary as strings of 0s and 1s. The aforementioned method will iterate as the number of generations.

SIMULATION MODEL AND CONTROL VARIABLES

The mathematical model of the Double-skin Façade system used a lumped simulation model developed by the previous study (Yoon et al, 2009) without any modification. Equation (2) describes a state space equation that is composed of state vector (x), state matrix (A), load vector (b), control variables (u), and time (t). And equation (3), (4) describe cost fuctions (equation (5)) shows the optimization problem.

$$\dot{x} = A(u,t)x + b(u,t) \tag{2}$$

$$J_{cooling\_mode} = \int_{t1}^{t2} (Q_{cv,rd} + Q_{sol,trans} + Q_{air})dt \tag{3}$$

$$J_{heating\_mode} = -\int_{t1}^{t2} (Q_{cv,rd} + Q_{sol,trans} + Q_{air})dt \tag{4}$$

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

where $Q_{cv,rd}$ is heat gain in the room space by convection and radiation on the interior glazing (W), $Q_{sol,trans}$ is the sum of transmitted direct and diffuse solar radiation (W), Q_{air} is heat gain in the room space by a beneficial airflow regime from cavity to the room space or outside (W), ϕ_{slat} is the blind slat angle (°), *AFR* is Air Flow Regime (dimensionless), and *OR* is the opening ratio of the ventilation damper (%) as shown in Figure 2.

The state vector consists of exterior/interior glazing temperature (x_1, x_2, x_3), blind slat temperature (x_4), air temperature in the larger cavity (x_5), and cavity air temperature (x_6) as shown in Figure 1. The control variables consist of blind slat angle, airflow regime, and opening ratio of the ventilation damper (Figure 2). The blind slat angle can rotate from 90° to - 90°. And the opening ratio of the ventilation damper is a continuous variable opened from 0% to 100%. However, *AFR* is a discrete control variable (Mode #1 ~ #2: inside circulation, Mode #3 ~ #4: outside circulation, Mode #5 ~ #8: a diagonal airflow, Mode #9 and Mode #10: open and closed four dampers).

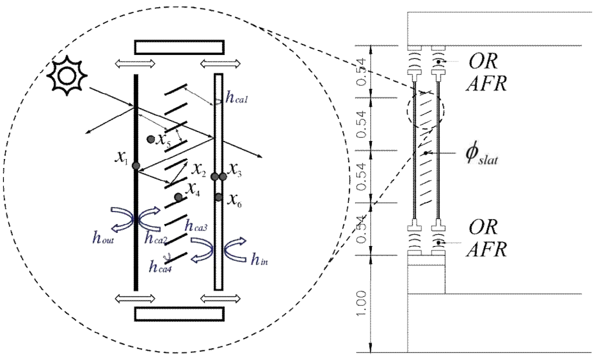
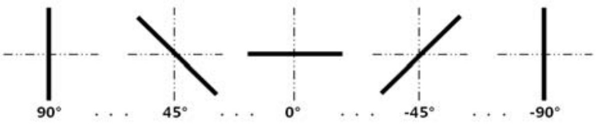
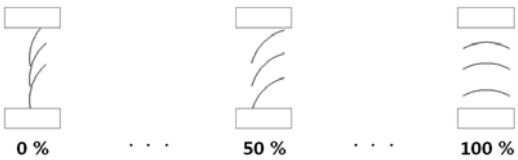


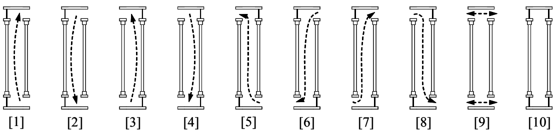
Figure 1. State variables and configuration of the Double-skin Façade



(a) Blind slat angle (ϕ_{slat} *)*



(b) Opening ratio of the ventilation damper (OR)



(c) Ten airflow regimes (AFR)

Figure 2. Control variables and constraints

The rule-based approach that was applied in this study is as follows: if solar radiation on the façade is above 150 W/m^2, blind slat angle gradually closes. If it is above 650 W/m^2, the blind slat angle fully closes. In addition, when cavity temperature is above 28°C, four dampers fully open (CIBSE, 1996).

The optimal control is mainly to search control variables by minimizing cost functions (equations (3) and (4)) based on heating/cooling mode as time horizon. As stated above, this study calculated optimal control variables over a time horizon of 15 minutes using four optimal control strategies (exhaust search, gradient-based search, GPS, and GA). For this study, input variables (wind direction, wind speed, cavity air velocity, solar radiation, exterior/interior pressure difference, exterior/interior glazing temperature, and ground temperature) are measured using sensing and data logging devices with the sampling time of one minute. In particular, the aforementioned data was gathered under a clear sky for 24 hours.

This study explains the GPS and GA in more detail in the following section because the previous study (Yoon et al, 2009) showed a detailed explanation with regard to integration of mathematical model and control strategies (exhaust search method and gradient-based method).

INTEGRATION OF OPTIMAL ALGORITHM AND SIMULATION MODEL

The optimization techniques are integrated with the lumped simulation model in MATLAB platform. The GPS used the patternsearch function, and the GA used the ga function in the MATLAB optimization toolbox.

The GPS (1) draws each point in the search process, (2) forms a set of points (called a mesh), (3) calculates the cost function, and (4) finds an optimal point in the mesh at each step. It should be noted that simulation users must determine a suitable mesh size to avoid convergence to local minima. This study selected a minimal vector length as 0.00001, and maximal vector length as infinite (default). The minimal vector length was obtained through three cycles of trial and error. To determine the mesh size, this study selected a polling method called GPSPositiveBasis2N in MATLAB optimization routines. The polling method assumes that each control variable is independent. N control variables constitute 2×N vectors .

Figure 3 shows the integration process of the lumped simulation model and GA. The GA process consists of the following five steps:

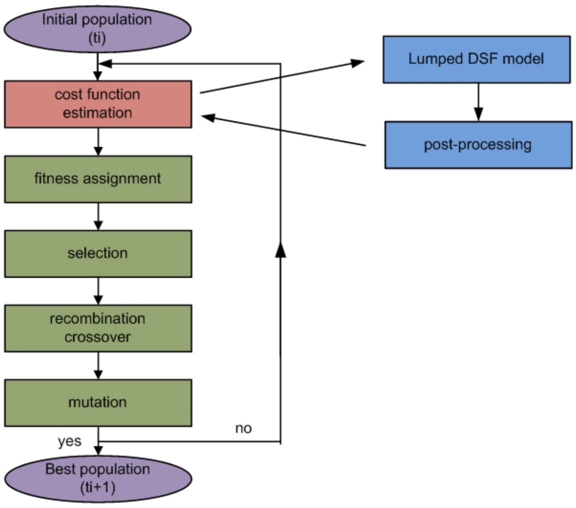


Figure 3. Integration of the GA with lumped simulation model

- *Initial population*: The control variables converted a chromosome of a binary number through the encoding process. This study generated 200 initial populations using trial and error.
- *Fitness assignment*: The selected initial population searches individuals to minimize energy flow of the Double-skin Façade using a cost function.
- *Selection*: This study used the tournament method to determine the fittest individuals of the initial population. In other words, the selection mechanism is a method to search for the best of the existing population.

- *Crossover*: The method probablistically generates new individuals by pairing up and swapping some of the genes. This study used the twopoint method, and a fraction value was selected as 0.8.
- *Mutation*: The mutation makes a new individual by forcing changes in a bit of gene with low probabilities of modification (from 0 to 1, or from 1 to 0). This study used the adaptfeasible method.

The above-mentioned methods are a process to find optimal individuals from the population. The optimization process iterates according to a fixed number of generations. In other words, the fittest individuals determined by one generation continuously iterate until finding the optimal solution. The number of generations was set at 500.

SIMULATION RESULTS

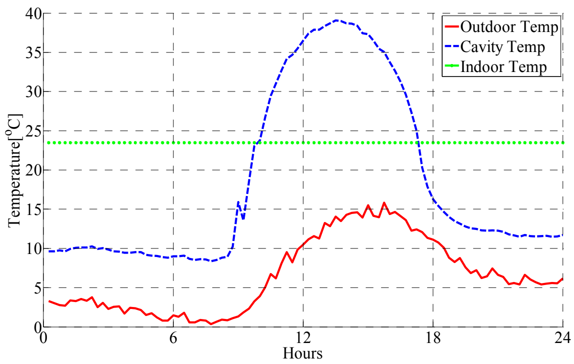
The simulation was performed during each day in heating mode (winter, January 7th) and cooling mode (summer, August 16th). The results are as follows.

Heating mode

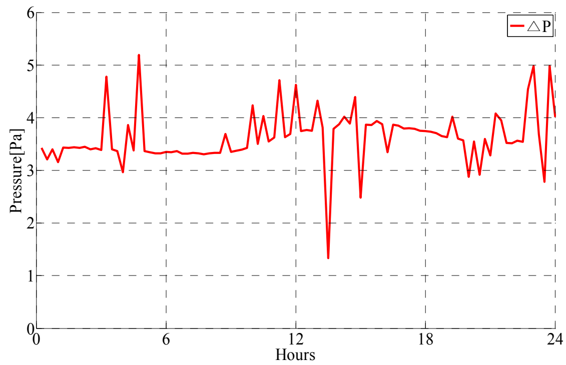
Figure 4 shows the blind slat angle, airflow regime, and opening ratio of ventilation dampers toward control strategies. The results show that the rule-based approach is inferior to the other optimal controls. The reason is as follows: (1) blind slat angle does not keep track of the solar altitude; (2) the other control variables maintain constant with *AFR* - mode # 10, the opening ratio of the ventilation damper – 0%. On the other hand, the optimal controls transport solar radiation indoors to minimize the cost function. In daytime, the optimal controls transmit solar radiation as much as possible by which the blind slat angle was quite similar to solar altitude. And in nighttime, it performs a role of radiation shield by which the blind slat angle is fully closed.

The airflow regime and opening ratio of the ventilation dampers showed a similar pattern among four optimal control methods. As shown in Figure 4(a), in daytime, the *AFR* operates with inside circulation (Figure 2(c), mode #1) due to high cavity temperature. It will decrease an indoor heating load by transmitting hot air through the cavity. In nighttime, a diagonal airflow (Figure 2(c), modes #5 and 6) is used.

As shown in Figure 5, the cause is that cavity temperature is higher indoor set-point temperature (23.5℃) and the room is pressurized ($\Delta p > 0$). In other words, the exhausted air warms the cold cavity to heat the facade system and thus reduce transmission losses.



(a) Air temperature (Indoor, outdoor, cavity)



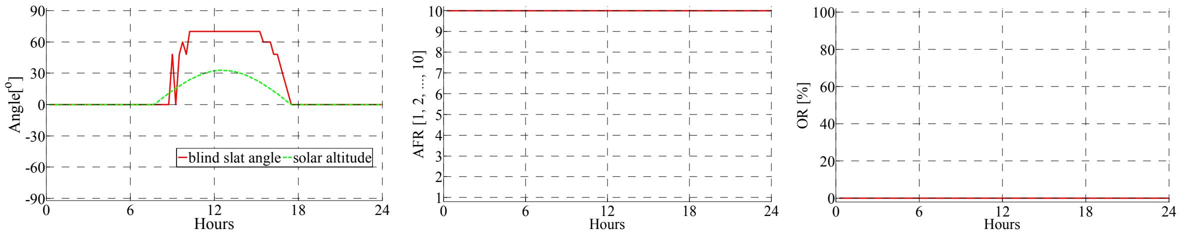
(b) Pressure difference (Indoor vs. outdoor)

Figure 5 Temperature and pressure difference

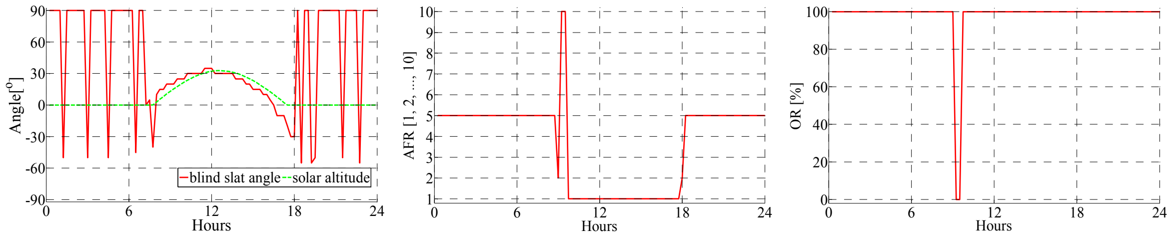
Table 1 compares the results of each control strategy. The optimal controls are superior to the rule-based approach. When comparing optimal controls, the difference is imperceptible (exhaust search method > GA > GPS > gradient method). The exhaust search called brute force must evaluate the cost function for all possible cases. If simulation users can acquire all possible combinations of control variables in advance, it will be highly probable to find the nearly global minimum (Yoon et al, 2009).

However, it may take much computation time by which the more cost function and sampling interval increase in numbers, the more the number of possible solutions increase exponentially. Regarding computation time, the average convergence time (time horizon: 15 min) is as follows: gradient-based method (0.18 sec), GPS (0.5 sec), and GA (120 sec) with an Intel i7-870 (2.93 GHz) and 6 GB of memory.

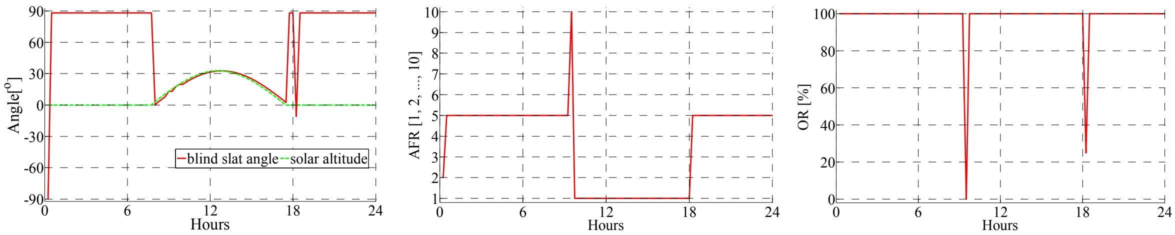
In the results, the GA had an advantage to discontinuous and non-differential problems, but took a long computation time for converging solution sets.



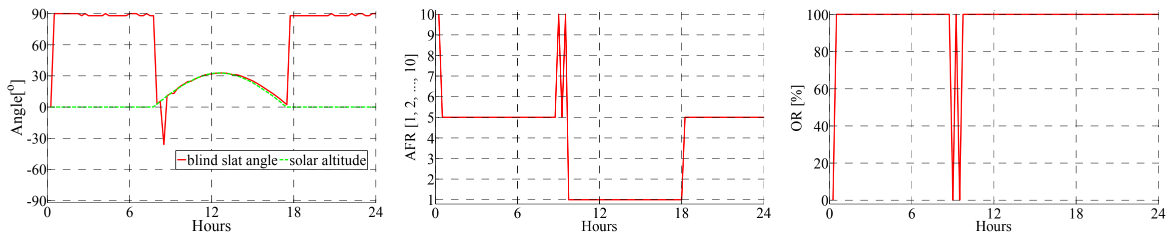
(a) Rule-based method



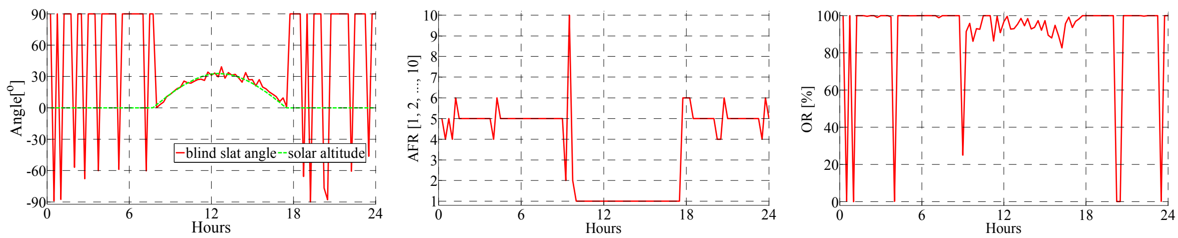
(b) Exhaust search method (interval of blind slat angle = 10°)



(c) Gradient-based method



(d) Generalized Pattern Search method



(e) Genetic Algorithm method

Figure 4 Results of control variables in heating mode (blind slat angle, AFR, OR)

Table 1

Comparison of cost function (heating mode)

	Rule-based	Optimal control			
		Exhaust search	Gradient	GPS	GA
$Q_{cv,rd}$	5.43	5.16	4.15	4.10	4.47
$Q_{sol,trans}$	2.69	8.33	8.90	8.97	9.15
Q_{air}	0.00	11.49	11.39	11.39	11.33
J_{heat}	**-8.12**	**-24.98**	**-24.44**	**-24.46**	**-24.95**

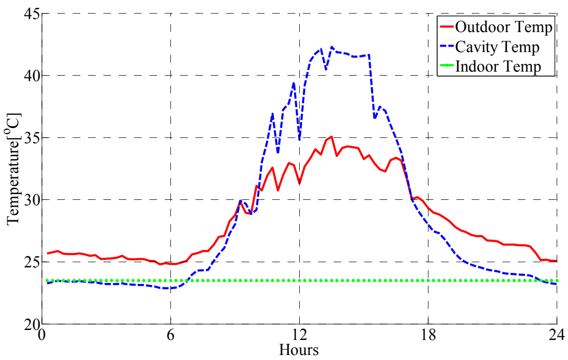
Cooling mode

Figure 6 shows simulation results of control strategies in cooling mode. Firstly, the results showed that optimal control could be far superior to the rule-based approach.

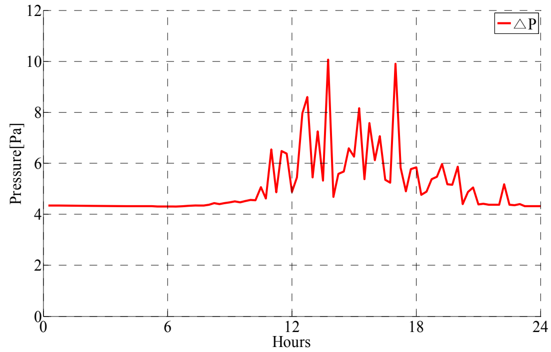
In daytime, the blind slat angle of the optimal control executes fully closed (blind slat angle of - 90° is identical to that of 90°, which is fully closed). In the summer, if blind slat angle is fully closed, it will be able to block out solar energy. Please be noted that daylighting autonomy is not considered in this study. Hence, the optimal slat angle is proved to be fully closed all the time.

In nighttime, the blind slat angle of the gradient-based approach and GPS keep horizontality (figure 2(a), angle: 0°), but exhaust search and GA keep fully closed the same as in daytime. It seems that the solutions converge to local minima.

In the opening ratio of the ventilation dampers, *AFR* is a diagonal airflow (Figure 2(c), modes #5 and #6). As shown in Figure 7, outdoor temperature is higher than indoor temperature (23.5℃), and indoor airflow exhausted the outside (indoor → cavity → outdoor) due to the pressurized state in the room ($\Delta p > 0$).



(a) Air temperature (Indoor, outdoor, cavity)



(b) Pressure difference (Indoor vs. outdoor)

Figure 7 Temperature and pressure difference

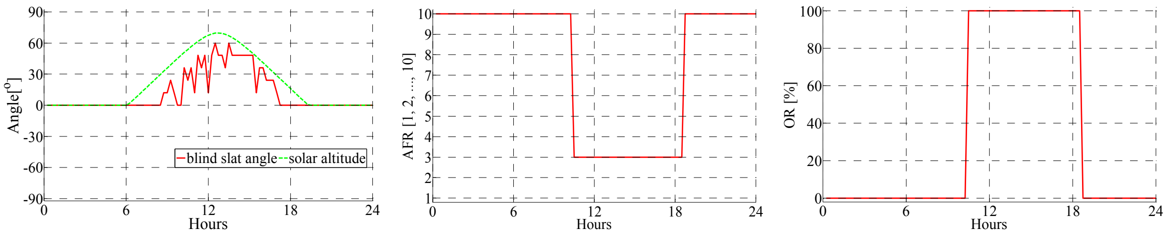
Table 2 shows comparison results of the cooling mode to each control strategy. In the results, the difference was imperceptible, except with the exhaust search method. The exhaust search method showed high heat gain in the room space by convection and radiation on the interior glazing than other control strategies. Compared with the computation time of average convergence as the time horizon, it is similar to the results of heating mode.

By the aforementioned results, GA is superior to other control strategies in terms of minimizing cost functions, but its difference is also imperceptible. In other words, considering computation time and cost function, the gradient-based approach and GPS are more advantageous to the other control strategies of the Double-skin Façade.

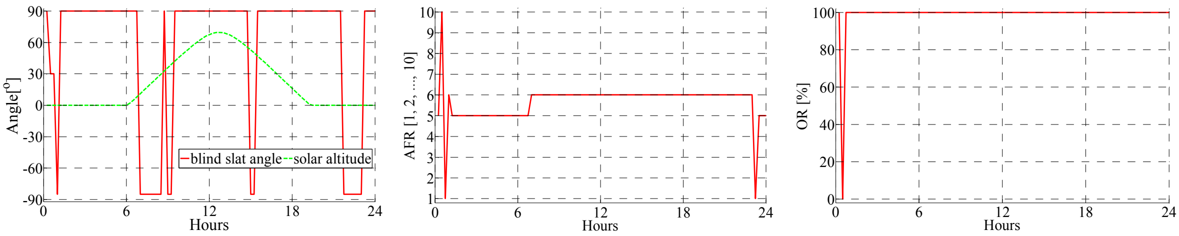
Table 2

Comparison of cost function (cooling mode)

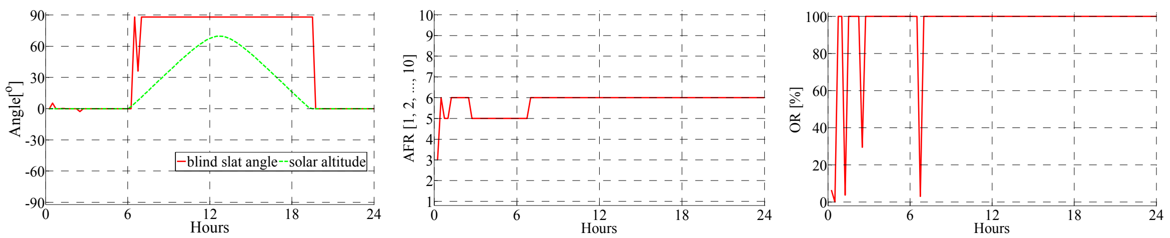
	Rule-based	Optimal control			
		Exhaust search	Gradient	GPS	GA
$Q_{cv,rd}$	5.98	2.13	0.91	0.89	0.83
$Q_{sol,trans}$	0.26	0.01	0.03	0.02	0.00
Q_{air}	0.00	0.00	0.00	0.00	0.00
J_{heat}	**6.24**	**2.14**	**0.94**	**0.91**	**0.83**



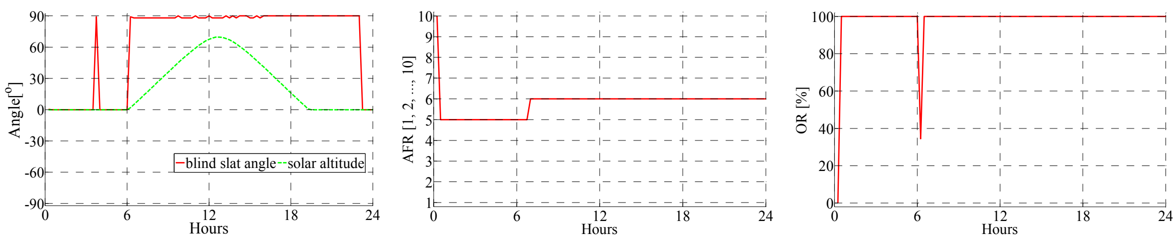
(a) Rule-based method



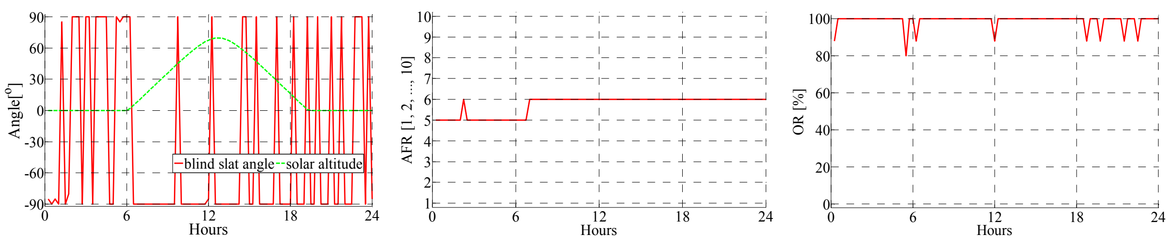
(b) Exhaust search method (interval of blind slat angle = 10°)



(c) Gradient-based method



(d) Generalized Pattern Search method



(e) Genetic Algorithm method

Figure 6 Results of control variables in cooling mode (blind slat angle, AFR, OR)

CONCLUSIONS

This study compared control strategies that consisted of rule-based approach (practical approach) and four different optimal control approaches (academic approach). In particular, this study analysed characteristics of the optimization algorithm and control results of the Double-skin Façade in addition to GPS and GA. The comparison results were as follows.

The optimal control was superior to the rule-based method in terms of cost function. It is because the rule-based method follows a set of rules (solar radiation, cavity temperature) regardless of dynamic characteristics of the Double-skin Façade. Among optimal controls, GA is superior to other control strategies, but its difference is imperceptible. It should be noted that GA needs the most computation time for convergence of the solution. In other words, the gradient-based method and GPS method are appropriate for optimal control of the Double-skin Façade in terms of cost function and computation time.

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