Multi-Objective Optimization of Energy Saving and Thermal Comfort in Thermo Active Building System based on Model Predictive Control

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ABSTRACT

Japan will have to further reduce CO_2 emissions to meet its obligations under the Paris Agreement negotiated at the 2015 United Nations Climate Change Conference. Society is increasingly demanding higher energy-efficiency standards and zero-energy buildings because general commercial buildings have high energy costs, especially for air conditioning. Furthermore, it is just as important to consider the productivity of the people working in these buildings; therefore, there is an urgent need for air-conditioning systems and control methods that are both energy efficient and provide thermal comfort. Radiant heating and cooling has been introduced in Japan in recent years. This is a means of creating an indoor thermal environment that balances energy efficiency and comfort in the office. A thermo-active building system (TABS) is an example of an advanced radiant heating and cooling system. TABS utilizes the building frame, which is mainly concrete slab, to store and radiate heat. Compared with a conventional radiant system, TABS offers higher energy efficiency, a more comfortable environment for workers, and cost advantages. ON/OFF or PID controls are commonly used to control conventional air conditioning; however, to optimize air-conditioning control, it is essential to include load prediction because the thermal response of the ceiling surface temperature is slow due to the ceiling's large thermal mass. The problem is that either energy consumption increases or thermal comfort decreases in cases where these controls are applied to TABS. In a previous study, we proposed using model predictive control (MPC), which takes into consideration thermal response, as a way of optimizing the control of TABS in an existing office building that also had an outdoor air processing unit. We verified the effectiveness of MPC by performing a coupled analysis using MATLAB/Simulink and CFD as a single-objective optimization method for optimizing thermal comfort; however, energy consumption was not considered in this previous study. Therefore, in the present study, we conducted a fundamental examination of multi-objective optimization of thermal comfort and energy efficiency by performing numerical simulations using MATLAB/Simulink. As the result this study suggests that it is possible to reduce the water flow rate of TABS while maintaining comfort by performing multi-objective optimization. A reduction effect of up to 68.3% was obtained in comparison with reference case.

KEYWORDS

Radiation air conditioning, Building thermal storage, TABS, MPC, CFD

1 INTRODUCTION

Japan will have to further reduce CO_2 emissions to meet its obligations under the Paris Agreement negotiated at the 2015 United Nations Climate Change Conference. Society is increasingly demanding higher energy-efficiency standards and zero-energy buildings because general commercial buildings have high energy costs, especially for air conditioning. Furthermore, it is just as important to consider the productivity of the people working in these buildings; therefore, there is an urgent need for air-conditioning systems and control methods that are both energy efficient and provide thermal comfort.

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Previous studies2) have attempted to dynamically control TABS using MPC by targeting half spans of a standard floor, and the effectiveness of this control method has been demonstrated by CFD analysis and numerical simulation using MATLAB/Simulink3). However, only single-objective optimization for thermal comfort was conducted in these analyses and energy consumption was not considered. Therefore, in the present study, we conducted a fundamental examination of multi-objective optimization of thermal comfort and energy efficiency by performing numerical simulations using MATLAB/Simulink.

2 MULTI-OBJECTIVE OPTIMIZATION

Previous studies have determined the optimal operating conditions in an indoor environment using an air handling unit (AHU) and TABS together. The ceiling surface temperature was controlled using MPC with the optimal operating conditions being the target values.

With multi-objective optimization, energy consumption increases when thermal comfort is prioritized and, conversely, thermal comfort decreases when energy consumption is reduced. Therefore, there is a trade-off between energy consumption and thermal comfort. This trade off means that multi-objective optimization is achieved by minimizing or maximizing multiple objective functions within given constraints4).

2.1 An optimization method5)

Multiple objective functions can be unified by using the multi-objective formulation shown in equation (2.1) in the multi-objective optimization problem. The optimal solution of the unified objective function is found using an optimization method.

$$\min f = \sum_{i=1}^{k} f_i \tag{2.1}$$

Furthermore, there is an infinite number of solutions in the solution space, as shown in Fig. 1. There will always be a set of solutions (Pareto solution) that are superior to other solutions for any of the objective functions where there is a trade-off. A set of such solutions, called a Pareto frontier, is a rational solution to multi-objective optimization problems. However, the preferred Pareto solution (e.g., optimizing energy consumption and comfort) differs according to what a given building is used for and what its design concept is; therefore, weighting6) is used in the optimization method in this research. In the method we used, each of the Pareto solutions is obtained by solving the weighted sum shown in equation (2.2) as a single objective function. A

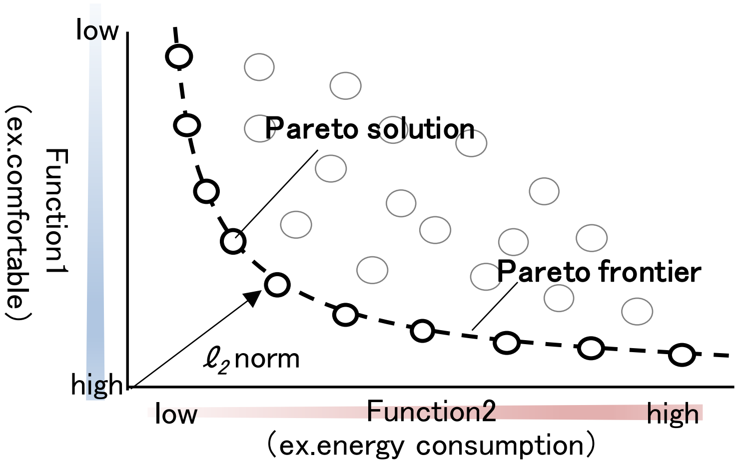

Figure 1: Image of Multi-Objective Optimization

decision maker determines the Pareto solution by setting a weighting for each objective function by using the weighting factor w.

$$\sum_{i=1}^{k} w_i = 1 \tag{2.2}$$

$$w_i \geq 0 \tag{2.3}$$

3 OUTLINE OF OPTIMAL CONTROL METHOD[7,8)]

We used MPC as the optimal control method in this report. MPC is a control method that determines the current value of the optimal manipulated variable pattern (i.e., the water flow rate) while predicting the behavior of a future controlled variable (i.e., the ceiling surface temperature). Equation (3.1) shows the evaluation function of MPC. As shown in Fig. 2, H_p represents a prediction horizon, H_u represents a control horizon, and $w^y, w^u, w^{\Delta u}$ represent different weightings. The first term indicates the deviation of the prediction control output $\mathrm{y}(k+i|k)$ from the reference trajectory $y_{ref}(k+i|k)$, and any deviation is penalized. The initial point of $\mathrm{y}(k+i|k)$ is the output measurement value $y(k)$. The second term is penalized for its deviation from the ideal static value of the input. The third term is penalized for deviating from the control move $\Delta\mathrm{u}(k+i|k)$. In addition, constraints of equations (3.5) and (3.6) are required in order to use the weighting method. Equation (3.1) is a convex function, which is a standard optimization problem known as a quadratic programming problem. z_k shows the manipulated variable in each step within a prediction horizon. An optimal solution is obtained by minimizing the evaluation function $J(z_k)$ by using the least squares method. Each term is an *l2* norm (Euclidean norm) and also called an *l2* norm optimal control problem[9)].

$$J(z_k) = J_y(z_k) + J_u(z_k) + J_{\Delta u}(z_k) \tag{3.1}$$

Where

$$J_y(z_k) = \sum_{j=1}^{n_y} \sum_{i=1}^{H_p} \{\frac{w_{i,j}^y}{S_j^y}[y_{ref}(k+i|k) - y_j(k+i|k)]\}^2$$

$$J_u(z_k) = \sum_{j=1}^{n_u} \sum_{i=0}^{H_p-1} \{\frac{w_{i,j}^u}{S_j^u}[u_j(k+i|k) - u_0]\}^2$$

$$J_{\Delta u}(z_k) = \sum_{j=1}^{n_u} \sum_{i=1}^{H_p-1} \{\frac{w_{i,j}^{\Delta u}}{S_j^u}[u_j(k+i|k) - u_j(k+i-1|k)]\}^2$$

$$z_k^T = [u(k|k)^T \;\; u(k+1|k)^T \;\; \cdots \;\; u\left(k+H_p-1\middle|k\right)^T]$$

Subject to

$$\Delta\underline{u} \leq \Delta u(k) \leq \Delta\overline{u} \tag{3.2}$$

$$\underline{u} \leq u(k) \leq \overline{u} \tag{3.3}$$

$$H_p > H_u \tag{3.4}$$

$$w_{i,j}^y + w_{i,j}^u + w_{i,j}^{\Delta u} = 1 \tag{3.5}$$

$$w_{i,j}^y, w_{i,j}^u, w_{i,j}^{\Delta u} \geq 0 \tag{3.6}$$

n_v: Number of plant output variables, n_u: Number of manipulated variables,
k: Current control interval, y_{ref}: Reference value for jth plant at ith prediction horizon step
y_j: Predicted value of jth plant output at ith prediction horizon step, u: manipulated variables
u_0: Initial value of manipulated variables(MV), S_j^y , S_j^u: Scale factor tor jth output, MV(= 1)
$w_{i,j}^y, w_{i,j}^u, w_{i,j}^{\Delta u}$: Tuning weight for jth output, MV, MV movement movement at ith prediction horizon step
H_p: Prediction horizon, H_u: Control horizon,
z_k : MV of each step in the predction horizon at current control interval

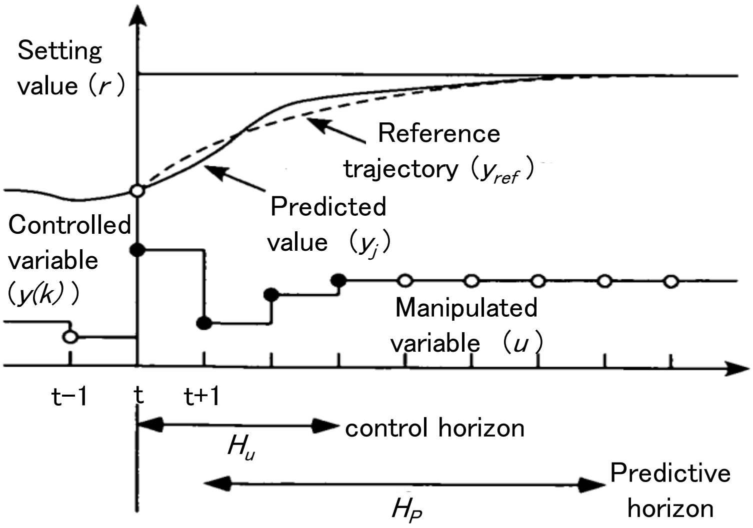

Figure 2: Image diagram of Model Predictive Control (MPC)

4 OUTLINE OF ANALYSIS

First, we used a Simulink analysis model whose effectiveness was demonstrated in previous research$^{2)}$ to conduct case studies in which multi-objective optimization using MPC was performed with manipulated and controlled variables that had been given various weightings.

4.1 Analysis case

The cases analyzed are shown in Table 1. Case 0 is a case that prioritizes comfort. Case 1 is a case in which the objective functions of comfort and the integrated water flow rate have the same weighting. Case 2 is a case in which the integrated water flow rate is prioritized by increasing the weighting of the manipulated variable. The weighting factor of manipulated variable movement is the same in all cases.

Table 1: Analysis cases

	Weighting factor			Remarks
	Control variable	Manipulated variable	Manipulated variable movement	
	w^y	w^u	$w^{\Delta u}$	
Case0	0.9	0.0	0.1	Comfort priority
Case1	0.45	0.45	0.1	—
Case2	0.3	0.6	0.1	Energy efficiency priority

4.2 Analysis model

A prediction model was created from a step response using CFD analysis that reproduced the office space. The CFD analysis model is shown in Fig. 3. The radiating part of the CFD analysis model has piping that was laid out at a 150-mm pitch on a 125-mm thick slab and was held in place with mortar and insulation. To improve the analysis accuracy, a multi-block, which is a mesh generation technique, was inserted only around the embedded piping. A time delay, which is a fluctuation that often occurs in the step response to a step input, was observed when acquiring the step response of TABS. Therefore, a prediction model that took into account this time delay was created to reproduce this actual phenomena with Simulink. Because TABS and an AHU thermally affect the ceiling surface temperature and room temperature, respectively, in real space, they are reproduced similarly in the Simulink analysis model. Lighting is not considered in this analytical model because the heat load is low.

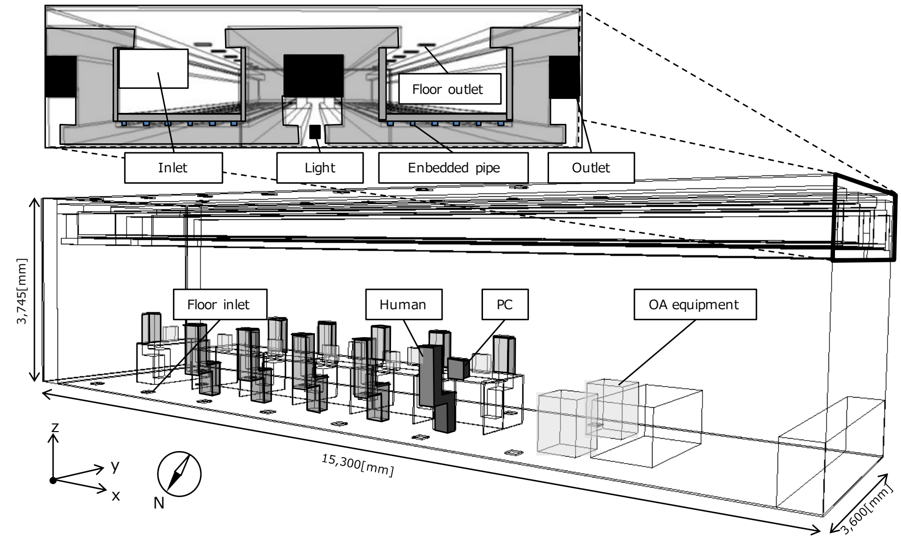

Figure 3: CFD analysis model

4.3 Analysis conditions

The analysis conditions in the Simulink are shown in Table 2. The load schedule is shown in Fig. 4. For the analysis period, the approaching period and the analysis period were each set to 1 day. PMV is used as an indicator of comfort. The average radiant temperature is affected by the ceiling surface temperature.

Table 2: Analysis conditions in Simulink

Prediction Model		Transfer function model
Sample time		TABS:1,800s, AHU:5s
H_p(Prediction horizon)		48step
H_u(Control horizon)		24step
Internal load	Human	6.8W/m^2
	OA equipment	5.6W/m^2
	Lighting	8.8W/m^2
Under floor air conditioning system	Flow rate	430~1,040m^3/h
	Air flow temperature	26℃
TABS	Water flow temperature	16℃
Constraints		
u(TABS)		$0 \leq u(k) \leq 4$
Δu(TABS)		$0 \leq \Delta u(k) \leq 4$
Weighting factor		$w^y + w^u + w^{\Delta u} = 1$
		$w^y, w^u, w^{\Delta u} \geq 0$

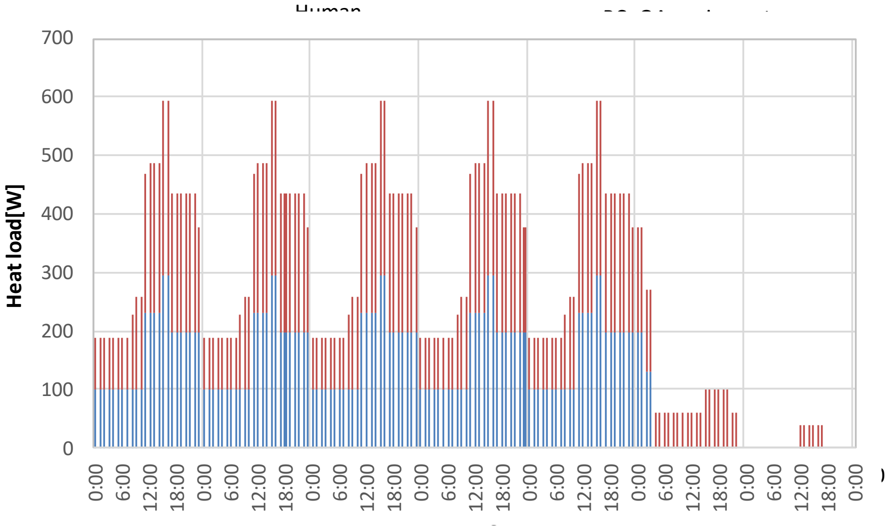

Figure 4: Load schedule

4.4 Analysis result

The results for the ceiling surface temperature and water flow pattern are shown in Fig. 5. The water flow rate is the largest in Case 0 because the weighting of the controlled value is large, but the ceiling surface temperature is controlled such that it is a constant target value of 24°C. The ability to maintain the target value becomes impaired as the weighting, w^u, of the controlled variable becomes larger. It was confirmed that, in all cases, the ceiling surface temperature stayed within the comfort range even though the water flow rate decreased. This suggests that the minimization of the water flow rate became important when the weighting of the controlled valuable was reduced. The control error in the target value of the ceiling surface temperature and the effect of reducing the water flow rate are shown in Fig. 6. The control error is the same as in Fig. 5. In addition, Case 2 has the lowest integrated water flow rate because the weighting of the manipulated valuable became large. A reduction effect of 30% in Case 1 and of 68% in Case 2 were obtained in comparison with Case 0. The above suggests that it is possible to reduce the water flow rate of TABS while maintaining comfort by performing multi-objective optimization using MPC.

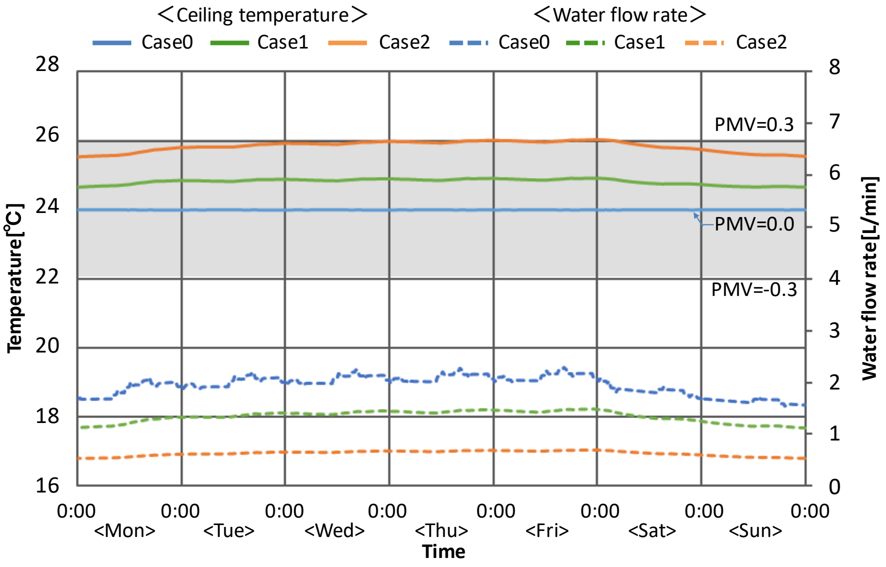

Figure 5: Analysis results on Simulink

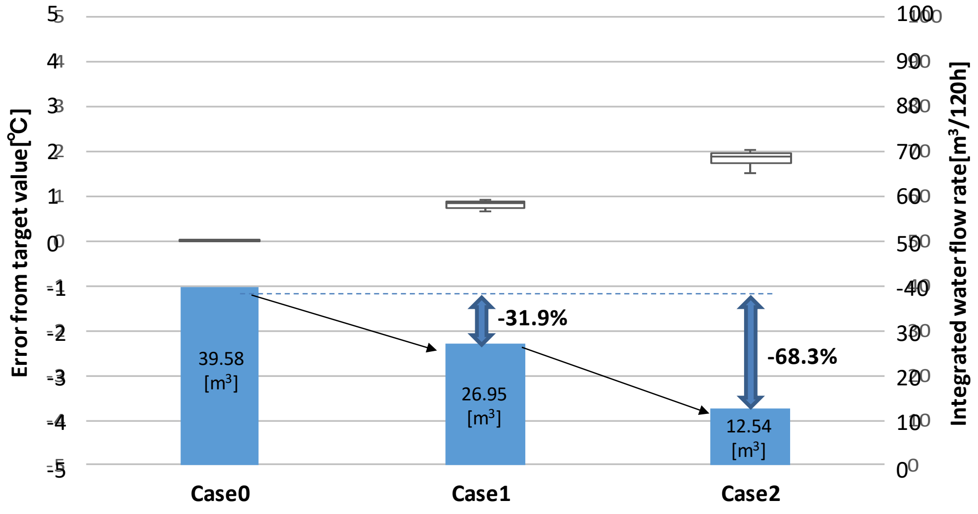

Figure 6: Control error and reduction effect of energy consumption

5 CONCLUSION

In the present study, we conducted a fundamental examination of multi-objective optimization of thermal comfort and energy efficiency by performing numerical simulations using MATLAB/Simulink. As a result, it is possible to reduce the water flow rate of TABS while maintaining the comfort by multi-objective optimization using MPC.

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