Optimal control of TABS in hot and humid regions

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ABSTRACT

In a previous study, an optimal control method was proposed for typical office space in hot and humid regions where Thermally Activated Building Systems (TABS) are installed. This method was based on a combination of load prediction, model predictive control, sparse modeling. The cooling capacity and indoor thermal environment were evaluated using computational fluid dynamics analysis and coupled MATLAB/Simulink analysis. However, that verification was conducted for one span (7.20 m×7.20 m×3.87 m) only, and verification on a larger analysis target is essential when considering implementation in actual buildings. Therefore, in this study, we proposed an optimal control method for a one-floor TABS model and verified it by co-simulation with Modelica and MATLAB/Simulink. The results showed that the proposed method improves the energy performance by reducing the integrated water flow rate while improving the control performance.

KEYWORDS

TABS, MPC, load prediction, sparse modeling, IDEAS

1 INTRODUCTION

In recent years, radiant heating and cooling systems have been widely adopted in Japan as a means for constructing a thermal environment that achieves both comfort and energy savings in office spaces, and the application of this technology is expanding[1)]. Furthermore, Thermally Activated Building Systems (TABS), in which the building structure is used to store and emit energy, are becoming increasingly popular. To date, TABS have been introduced mainly in Europe, and in recent years, attempts have been made to introduce them in Japan as well. TABS are expected to provide not only energy savings and comfort, but also benefits such as peak shifting, smaller heat and cooling sources, and cost reduction through the use of high thermal capacities. However, high thermal capacity means slow thermal response, and dynamic control methods are required to create a comfortable indoor thermal environment. Previous studies[2), 3)] have proposed an optimal control method using Model Predictive Control (MPC), which combines load prediction, its assimilation, and sparse modeling. The results of co-simulation with Computational Fluid Dynamics (CFD) and MATLAB/Simulink showed that the proposed method is effective for improving the control performance, energy efficiency, and sparsity of the transient output of air conditioners. However, analysis of TABS by CFD has been limited to a one-span (7.20 m ×7.20 m ×3.87 m) study due to the computational load and other factors. When considering implementation in actual properties, verification of control methods is essential because the objects to be analyzed

are large-scale. Among Building Energy Simulation (BES) methods, BES tools based on the Modelica language[4], which have been researched and developed mainly in Europe and the U.S. in recent years, are suitable for complex and large-scale objects due to their relatively low computational load and the ease of reusing the model.
Therefore, in this study, a one-floor TABS model was created using IDEAS[5)~7)], which was developed as a Modelica-based BES library. The effectiveness of an optimal control method that integrates previous knowledge was verified through a co-simulation with Modelica and MATLAB/Simulink (Figure 1).

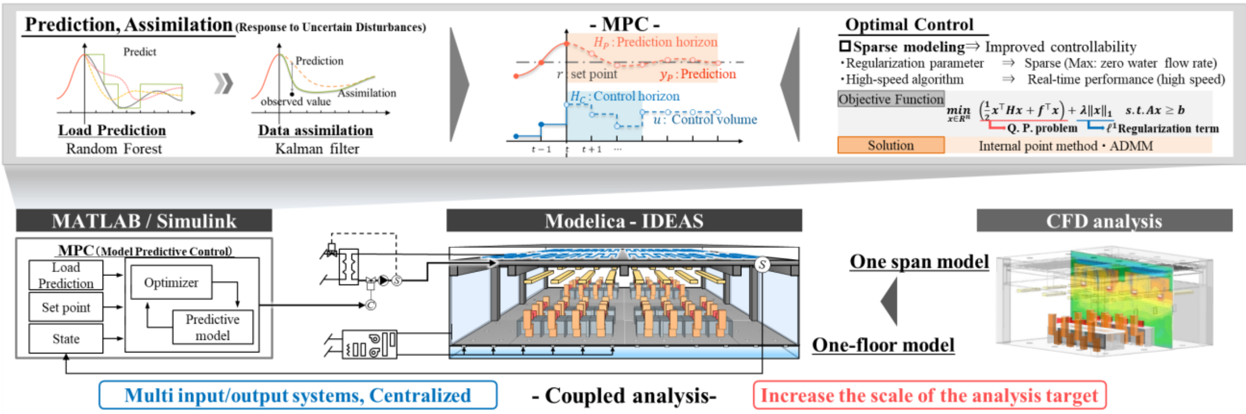

Figure 1: Outline of this study

2 ANALYSIS OVERVIEW

In this analysis, all zones were subjected to the same loading conditions (Human, Office Automation (OA) equipment: PC, Light), and the entire floor was controlled at once. The analysis was based on a one-floor TABS model created using IDEAS. The control method was MPC with sparse modeling (Sparse MPC), as proposed in a previous study. The co-simulation with MATLAB/Simulink and Modelica performed the verification of the control and energy efficiency.
Furthermore, assuming actual operation, it is conceivable that the load in each zone on the same floor is different. In such cases, the required thermal environment may also differ for each zone. To address such requirements, this study extended MPC and Sparse MPC to a centralized control method[8] for multi-input and multi-output systems and verified their effectiveness.

2.1 Analysis model

Figure 2 shows the IDEAS analysis model (1 floor). The analysis model was created for the interior (12 zones) and perimeter (18 zones) based on the 1-span model, which was confirmed to make accurate predictions. The perimeter zone was set to 0.5 spans, with exterior insulation in the exterior walls and windows with low-E double-glazing to make the building perimeter-less.

2.2 Analysis conditions

Tables 1 and 2 show the IDEAS and MPC analysis conditions. The analysis period was assumed to be August and its duration was 1 week each for the approach period and the primary analysis. In the IDEAS model, the heating values are given according to the loading schedule shown in Figure 3. MPC inputs the load with prediction and correction. Specifically, a load of Light and OA shown in Figure 3 was subjected to Random Forest prediction and Kalman Filter data assimilation. The target values of the ceiling surface temperature were analyzed by Modelica in advance and set to 25.5°C (high-load range for total control and centralized control) and 26.0°C (low-load range for centralized control), which satisfies the comfort zone.

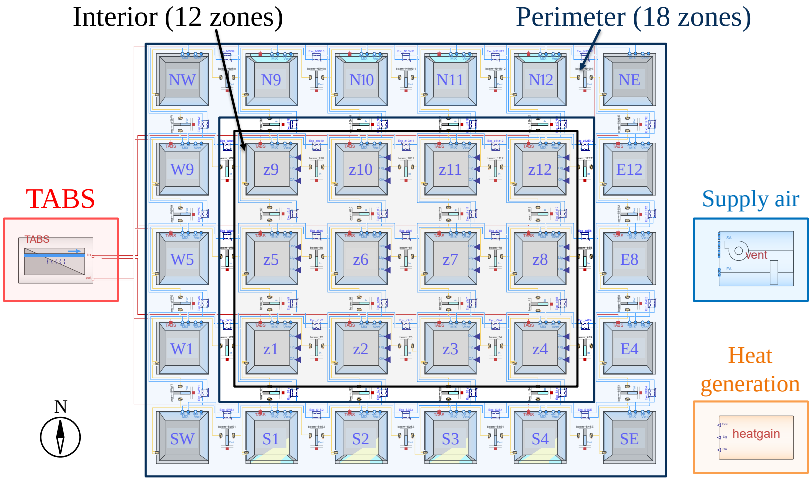

Figure 2: IDEAS analysis model (1 floor)

Table 1: Analysis condition of IDEAS

Weather data		Tokyo, Japan [9)]
Discretization method		Finite volume method
TABS	Water supply, Temperature	4 L/min, 16 ℃
Ventlation	Flow rate, Supply temperature	480 m³/h, 22.5 ℃ (day time), 26.0 ℃(night time)
Heat generation		Human (16 persons):69W/person, OA (16 units):32W/unit, Lighting (16 lights):60W/unit

Table 2: Analysis condition of MPC.

Prediction Model		State space model
Sample time		1step = 3,600s
Prediction horizon		24 step
Control horizon		12 step
Heat generation (Disturbance)		Same as IDEAS analysis
Water supply temperature in TABS		16 ℃
Constraints	u [L/min]	$0 \leq u \leq 4$
	Δu [L/min]	$-4 \leq \Delta u \leq 4$
	y [°C]	$25.0 \leq y \leq 26.0$ (Weekday Work Hours)
		$25.5 \leq y \leq 26.5$ (Weekday Work Hours (Low-load zone))

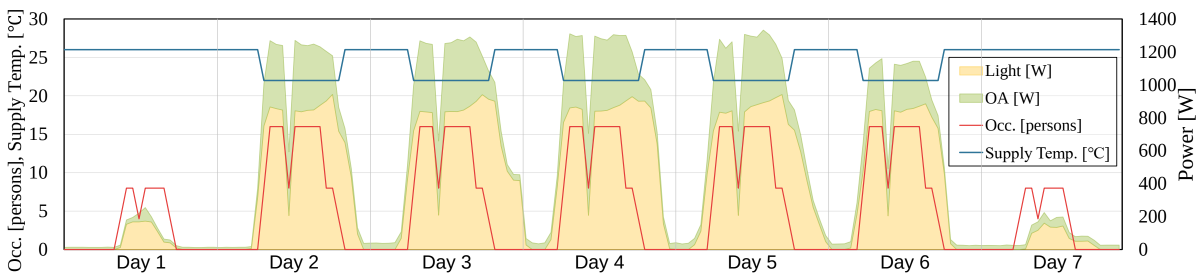

Figure 3: Supply Temp. and Power schedule

2.3 Analysis case

Table 3 shows the analysis cases: in Case 1, the entire floor was integrally controlled under the same load conditions in all zones and in Case 2, the analysis was performed by varying the load in each zone to account for the unevenness of the load. Based on the schedule in

Figure 3, the center of the floor (z6, z7) was set to high load (100%), the four corners (z1, z4, z9, z12) to low load (10% of high load), and the remaining interior zones to medium load (50% of high load). In all cases, on/off control was used during the approach period, and the control method was changed during this analysis period.

Table 3: Analysis Case

Case	Load	Control Method	Load prediction	Sparse
Case1-0	All the same load	ON/OFFcontrol	-	-
Case1-1		MPC	○	-
Case1-2		Sparse MPC	○	○
Case2-1	Different loads by zone	Overall control (MPC)	○	○
Case2-2		Centralized control (MPC)	○	-
Case2-3		Centralized control (Sparse MPC)	○	○

3 ANALYSIS RESULTS

3.1 Case 1: Effect of implementing sparse modeling

Figure 4 shows the time series of the water flow rate in Case 1. In Case 1-1, operation at a low flow rate occurred, but in Case 1-2, where sparse modeling was introduced, the low-flow operation was suppressed. This result indicates the potential to reduce the energy consumption of the heat source. During this analysis period, the percentage of zero water flow rate was 53.0% in Case 1-1 and 61.3% in Case 1-2, indicating that the introduction of sparse modeling expanded the time range of zero water flow rate.

In addition, the thermal environment deviated significantly from the target value on Day 2 of Case 1-0, but in Cases 1-1 and 1-2, where MPC was used, it followed the target value during the control period from Day 2 to Day 6.

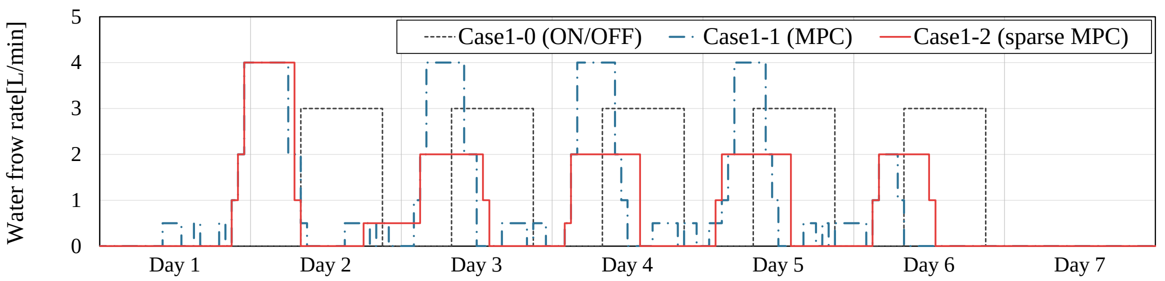

Figure 4: Change over time in the water flow rate in Case1

3.2 Case 2: Overall control versus centralized control

Figure 5 shows the Root Mean Square Error (RMSE) of the ceiling surface temperatures and the target in Case 2. Case 2-1 has zones with large error variations, while in Cases 2-2 and 2-3 which installed the centralization control method, the control error in each zone is smaller. Figure 6 shows the time series of water flow rate in Case 2. In Cases 2-2 and 2-3, water is supplied at the same flow rate as in Case 2-1 in the high-load zones, and a lower flow rate in the other zones. Figure 7 shows the integrated water flow rate in Case 2. On all days, the flow rates in Cases 2-2 and 2-3 are lower than in Case 2-1. In addition, the cumulative value for 1 week is reduced by about 35.0% in Case 2-2 and 35.8% in Case 2-3 compared with Case 2-1. These results indicate that the centralized MPC reduced the integrated water flow rate.

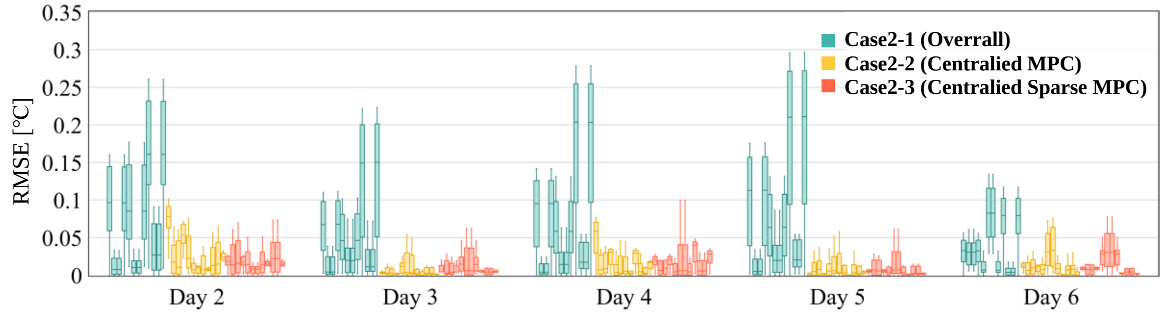

Figure 5: RMSE of the ceiling surface temperatures and the target in Case 2

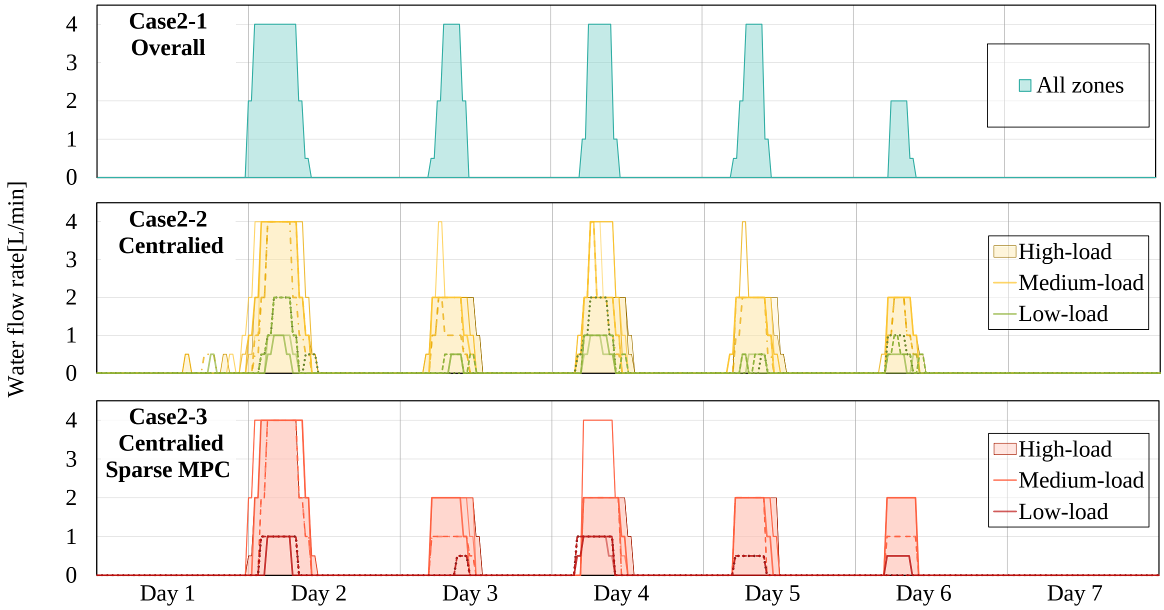

Figure 6: Change over time in the water flow rate in Case2

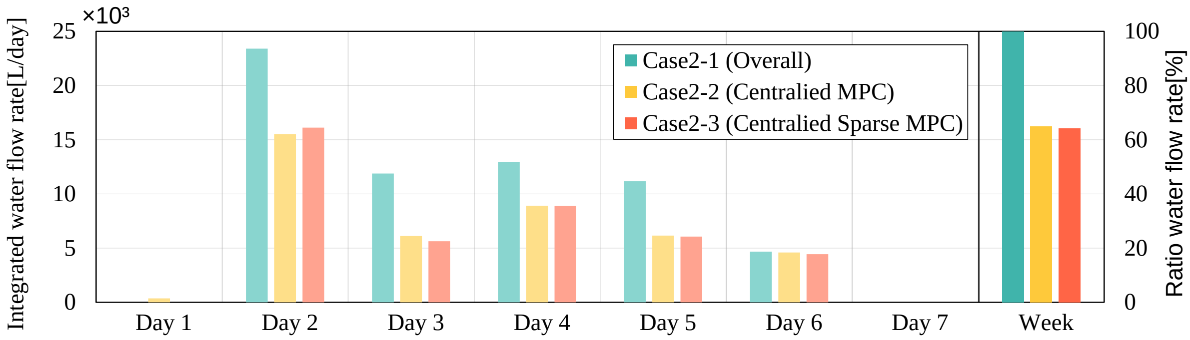

Figure 7: Integrated water flow rate in Case 2 (12 zone)

4 CONCLUSIONS

In this study, we proposed an optimal control method that integrates our previous findings for a one-floor TABS model. In addition, the performance was verified by co-simulation of Modelica and MATLAB/Simulink.

1) Even for a one-floor model created in IDEAS, it is possible to improve control performance while reducing the integrated water flow rate at each zone and time by introducing sparse modeling into MPC and performing centralized control.
2) By introducing sparse modeling into MPC, the time range of zero water flow rate was expanded for both overall control and centralized control. This result indicates the potential to reduce the energy consumption of the heat source.

3) By using the proposed and verified methods, it is also possible to study the optimal control of TABS in consideration of energy management (e.g., demand response) in multiple buildings, in addition to studies for multiple floors and entire buildings.

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