Coupling of Building Data Analysis and Building Simulation - Case Study in Large-scale Complex Building -

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Abstract

This study searches for energy saving measures and quantifies their potential by analyzing detailed energy and environmental data measured at a large scale complex building. Based on the results, the primary energy saving potential of these measures was quantified by coupling the calculation of energy saving measures' effect with a heat source system simulation, because the energy saving measures change the heat load of the building and affect the coefficient of performance (COP) of the heat source system. Four energy saving measures on the tenant side and two measures on the heat source system were identified, and 8.7% of the primary energy consumption potential was estimated by implementing all measures, even in a newly constructed energy-efficient building. The effect of the combination of the data analysis and simulation is not significant in this case study. The relationships between "big data" analyses and building performance simulations are also discussed in this paper since the high-resolution operation status of the equipment, the environmental conditions and occupants' behavior data will be available in the near future.

Introduction

Recent progress in sensing, as well as in information and communication technology, has facilitated the acquisition of the high-resolution operation status of every appliance/equipment, indoor/outdoor environment condition, and occupants' behavior in a building. The relationship between a building performance simulation and a data measurement/analysis must be re-defined, because measured data in the near future will have almost the same time and spatial resolution as the building performance simulation result.

In the design phase of buildings and building energy systems, the role of the building simulation is assumed to be generally unchanged. However, the following two points should be considered.

1. The building simulation will support not only the design of the building and equipment but also the design of the measurement system and the control system (Murai et al., (2012)).
2. Approximation, assumption and simplification of boundary conditions for building simulation, such as occupants' behavior, are set in the design phase and can be verified in the operation stage. Therefore, the simulation in the design phase should be kept as a detailed record of these conditions for verification after the completion of building construction. (Maile, et. al. (2012))

In the operation phase, high-resolution measurement data will dramatically change the role of the building performance simulation. So far, the building performance simulation in the operation stage has been verified by macroscopic data, such as energy consumption of a whole building. In near future, it will be verified and calibrated by the measured data with same order of resolution. The building performance simulation has also been used to examine relationships between various kinds of parameters and the whole system behavior, or to estimate higher-resolution energy consumption and indoor environment information. The latter role might be substituted by the measurement.

In the first part of this paper, the new relationships between "big data" from a building energy management system and the building performance simulation are discussed. Then, a case study of the combination of a big data analysis with a building performance simulation for optimization of operation in a large-scale complex building is reported.

Combination of data analysis and simulation in operation stage of building

Progress in sensing, as well as information and communication technology, enables us to obtain huge amounts of data from buildings in an efficient, prompt and cost-effective manner. Analysis of the obtained "big data" provides more valuable information for optimum operation and fault detection of building energy systems.

Recently, the concept of "cyber-physical systems" (CPS) has been evolving. According to the National Science Foundation (2016), "Cyber-physical systems are engineered systems that are built from, and depend upon, the seamless integration of computational algorithms and physical components." A building energy management system that has a detailed data sensing system and a building simulation tool is a typical example of a CPS.

However, the methodology of the CPS in building performance management still needs to establish a more specific guideline of information acquisition from a

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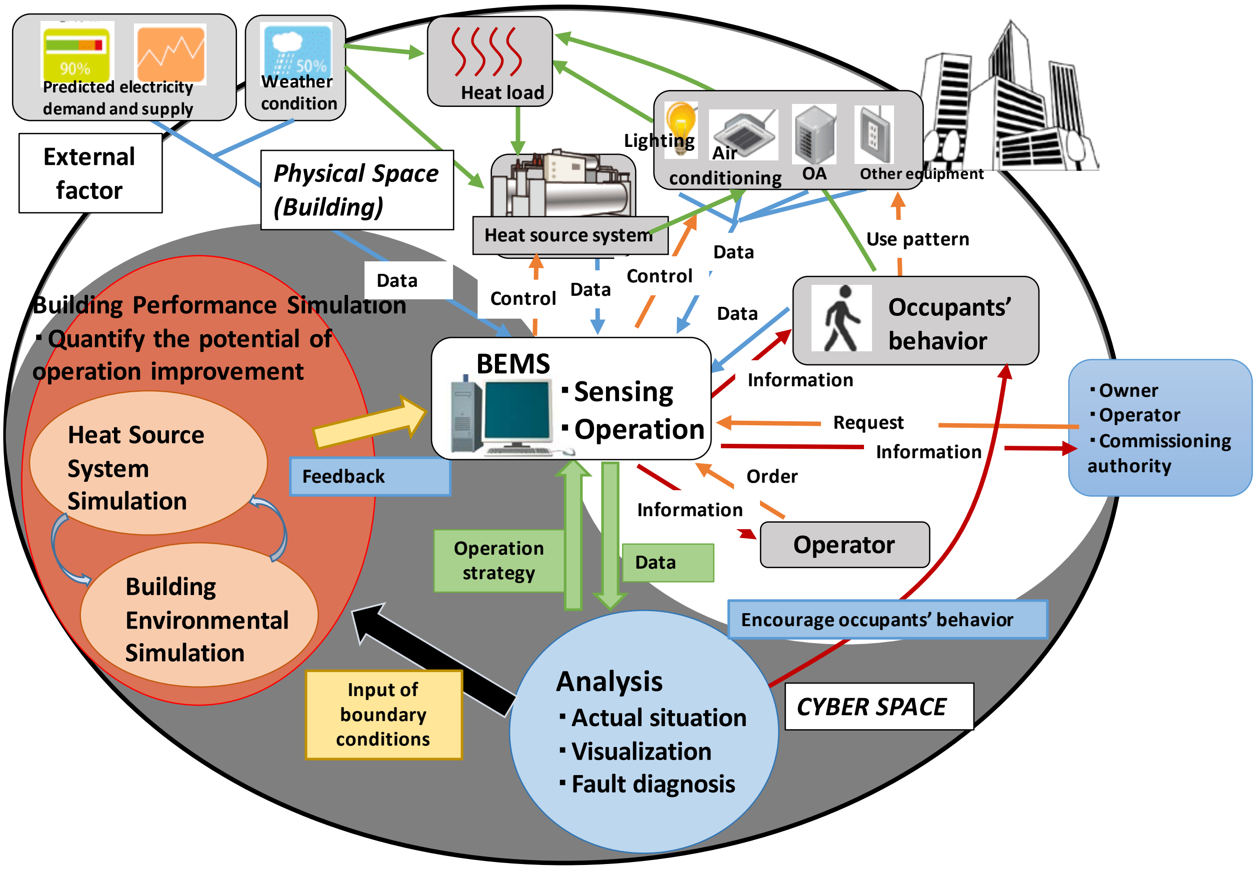

Figure 1. Concept of cyber-physical system in building

physical space (e.g., building and building equipment), an analysis procedure of data, and the positioning and objective of building performance simulations using these data. In addition, the CPS methodology needs to apply these results to the physical space. All of these requisites represent the "Cyber Space" side of the building energy and the environmental management system. Figure 1 shows the concept of the CPS of a building energy system.

Big data analysis provides useful information, such as optimum operation parameters and faults of the HVAC system, occupants' behavior, and actual efficiency of equipment (Hong, et. al., (2014)). However, to quantify the potential improvement of the whole system, a building performance simulation is required, because many cause-and-effects conditions exist in building energy and environmental systems. In this context, the effective combination of the data analysis and the building performance simulation becomes a key issue. For example, the following are included for chiller operation:

1. Calibration of the relationship between the coefficient of performance (COP) and the condensation temperature or the part load by measured data (Shimoda et. al., (2009)).
2. Simulation and data assimilation consider the more detailed physical mechanism of a chiller, such as the state of the refrigerant.

For an indoor thermal environment, the following are included:

1. Validation of the heat load simulation with the measured occupants' behavior and internal heat gain from (energy consumption of) appliances and lighting.
2. Assimilation of the computational fluid dynamics (CFD) results by the measured detailed distribution of air temperature and air velocity.

The most advanced procedure might be a whole building simulation and assimilation with all measured data (Raftery et. al. (2011), Royapoor and Roskilly (2015), Yang et. al. (2016)). However, this procedure has a huge computational load when resolution of measured data becomes high. Especially, simulation of an indoor system and an indoor environment for all rooms of a building has a heavy calculation load. In this paper, therefore, a simulation is applied only for the heat source system, while other HVAC systems and indoor environmental systems are examined by data analysis. The procedure is shown in Figure 2. In this procedure, the heat load change by implementing energy saving measures is considered in the simulation of the heat source system (Hattori et. al., (2011)).

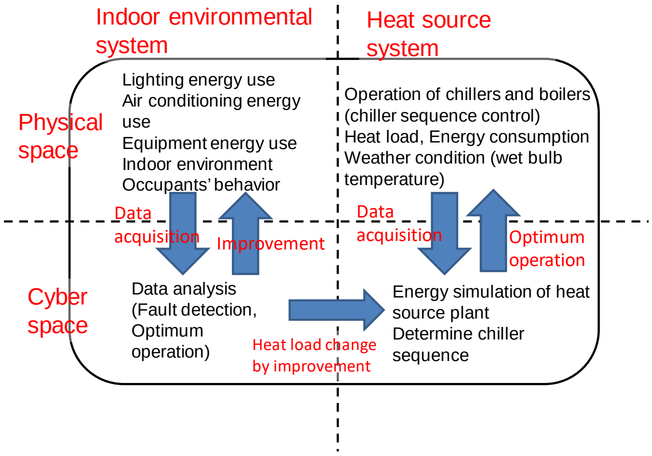

Figure 2. Procedure of energy management in this study

In addition, detailed data measurement enables us to calculate a more reasonable energy efficiency index. So far, "energy consumption per floor area" has been used for the energy efficiency metrics of a building. However, this index is disadvantageous in that it ignores the quality and amount of service provided to occupants and the effectiveness of occupants' sensing and control systems. If the number of occupants and the indoor environment can be measured, a more appropriate index, such as "energy consumption per occupant" or "energy consumption per occupant with unit service", can be calculated.

Outline of Case Study Building

Building and building energy system

A large-scale complex building located in Osaka, Japan was selected as the case study of this paper. The total floor area of the building is about 300,000 m^2. An outline of the building is shown in Table 1. The building consists of offices, retail stores, cafes, restaurants, etc. Heat source systems are located underground and on the rooftop separately to reduce power consumption of the cold/hot water pumps. The list of heat source equipment is given in Table 2. Air conditioning in the office area is provided by an outdoor-air processing unit (OPU) and an air handling unit (AHU) with a variable air volume (VAV) system. In the commercial area, the air conditioning system consists of an outdoor-air processing unit and a fan coil unit (FCU) for each tenant.

Table 1. Outline of building

Location	Osaka City, Osaka Prefecture, Japan
Number of stories	38 stories above ground level/ 3 stories underground
Total floor area	ca. 300,000 m^2 (Office area: 110,000 m^2, Commercial area: 16,300 m^2)
Major use	Office, Retail stores, Cafes, Restaurants, Convention

Table 2. Equipment list of heat source system

<table>
<tr><th>Location</th><th colspan="2">Model</th><th>No.</th><th>Cooling capacity [kW]</th><th>Heating capacity [kW]</th></tr>
<tr><td rowspan="3">Rooftop</td><td colspan="2">Gas absorption chiller</td><td>6</td><td>15,402</td><td>11,646</td></tr>
<tr><td colspan="2">Screw chiller</td><td>1</td><td>2,080</td><td>-</td></tr>
<tr><td colspan="2">Boiler</td><td>5</td><td>-</td><td>4,650</td></tr>
<tr><td rowspan="4">Underground</td><td rowspan="2">Brine turbo chiller</td><td>Ice-making operation</td><td rowspan="2">2</td><td>3,860</td><td>-</td></tr>
<tr><td>Cooling operation</td><td>5,274</td><td>-</td></tr>
<tr><td colspan="2">Inverter turbo chiller</td><td>2</td><td>7,032</td><td>-</td></tr>
<tr><td colspan="2">Ice thermal storage tank</td><td>2</td><td>5,280[max]</td><td>-</td></tr>
<tr><td colspan="3">Total capacity</td><td>-</td><td>33,648</td><td>16,296</td></tr>
</table>

Outline of measurement system

This building has a cutting-edge Building Energy Management System with about 60,000 measurement points of energy, flow rate, temperature and other physical parameters. Electricity use for lighting, fans and other equipment, and heat consumption are measured in each AHU zone (office area) and in each tenant (commercial area). This system was originally developed to enhance energy saving activities of tenants by visualization of data and commissioning of heat source systems, but the data of each tenant is also valuable to identify the potential of additional energy efficiency measures. The time interval of measurement for most points is one hour. In this paper, measured data from April 1, 2014 to March 31, 2015 is analyzed.

Searching energy saving potential in each tenant

By analyzing hourly data of each tenant, the following four items that have potentials of additional energy saving were found and the energy saving potential of each item was quantified as follows.

Optimization of supply air temperature of OPU and AHU in the office area

In the office area, cooling and heating are provided by the OPU and the AHU. From the data analysis, it was sometimes observed that the AHU operated in the cooling mode while the OPU operated in the heating mode, as shown in Figure 3. The reverse was also taking place. This mixing loss is supposed to be an after-effect of a room temperature set particularly high or low, and can be resolved by optimizing the supply air temperature of the OPU.

In this case, the hourly cooling/heating loads of the OPU and the AHU are compared, and the smaller amount is considered as a mixing loss and this amount is subtracted from both loads of the OPU and the AHU. Heating load of the OPU may contain some humidifying load, but it is ignored in this calculation. By implementing this calculation throughout the office area and year, the total heat load saving potential by this optimization can be estimated.

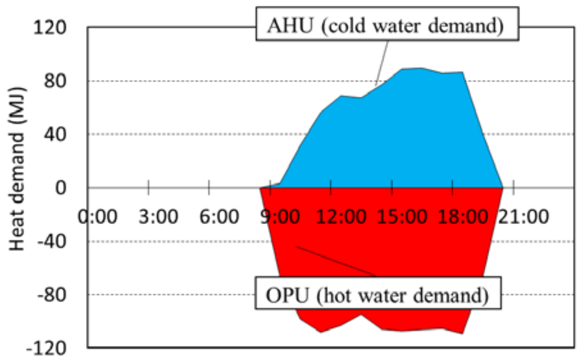

Figure 3. Reverse mode operation (11th February 2015)

Optimization of FCU and OPU in the commercial area

In the commercial area, cooling and heating are provided by the OPU and the FCU. As in the office area, simultaneous reverse mode operation between the FCU and the OPU in the commercial area was observed from the measurement data analysis result. Figure 4 shows an example.

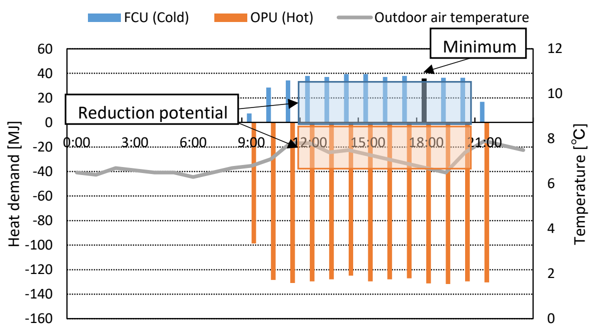

Figure 4. Reverse mode operation between FCU and OPU (16th December, 2014)

It is assumed that the set supply air temperature is optimized on a day-by-day basis since it is difficult to change the set supply air temperature of the OPU every one hour by the present control system,.

To exclude the duration of rise and decay, only the duration from 12:00 to 20:00 is considered. The minimum heat consumption of the FCU in this period is defined as excess heat consumption, and this amount is subtracted from both the OPU and the FCU. By implementing this calculation throughout the commercial area and year, the total heat load saving potential by this optimization can be estimated. As well as office area, the existence of humidifying load is ignored.

Avoidance of hunting of FCU in commercial area

From the time-series cold and hot water consumption of the FCU, the hunting phenomenon, which means that both cooling and heating modes occur alternately, is rarely observed, as shown in Figure 5. Hunting occurs with oversizing of the FCU. Calibrating the controlling parameters of the FCU is expected to reduce the excessive heat load.

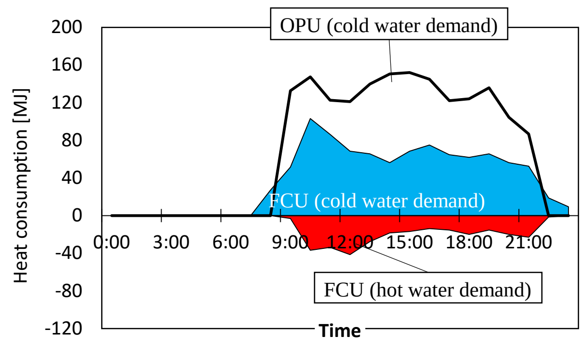

Figure 5. Example of hunting phenomenon in FCU. (11th August, 2014)

Hunting is diagnosed when both hot and cold water are consumed in the same FCU in one hour. The potential reduction of the heat demand is estimated by assuming that the smaller amount of heat consumption can be deducted from both the heating and the cooling loads. As shown in Table 3, about 10% of the heat consumption by the FCU in the commercial area could be reduced by eliminating hunting.

Table 3. Potential of heat demand saving by eliminating hunting

	Potential saving	Reduction rate*
FCU cool water demand	605	5%
FCU hot water demand	853	31%
Total	1458	10%

*Reduction rate is calculated based on total FCU heat consumption in the commercial area.

Encouragement of VAV use in commercial area

In the commercial area, the variable air volume (VAV) system, which controls the volume of outdoor air in high mode or low mode, was installed in each tenant of the commercial area. However, it was observed that most tenants fixed it in high mode. By encouraging tenants to change to low mode on weekdays when number of occupants is small, the heat load and power consumption of the fans can be reduced. The heat load reduction by using low mode is calculated by eq.(1) and eq.(2). Reduction of electricity use of the fan is calculated by eq.(3).

$$q_{out} = q_{ac} - \rho c_p Q_1 \Delta T \qquad (1)$$

$$\Delta q = q_{out} - q_{out} \times \left(\frac{Q_2}{Q_1}\right) \qquad (2)$$

$$\Delta W = \left\{1 - \left(\frac{Q_2}{Q_1}\right)^3\right\} \times W_1 \qquad (3)$$

q_{out} Thermal load of outdoor air.
q_{ac} Heat consumption of OPU.
ρ Density of air.
c_p Specific heat of air.
Q_1 OPU air volume in current situation.
ΔT Temperature difference between the supply air temperature and the set indoor temperature.
Δq Reduction of heat load of outdoor air.
Q_2 OPU air volume of the low mode.
ΔW Reduction of the power consumption of fan.
W_1 Fan power consumption of current situation.

Table 4 shows the result of the calculated energy saving by using the VAV system in low mode on weekdays. The largest reduction effect is obtained in the hot water demand, because the outdoor air load is dominant in the heating load.

Table 4. Summary of calculated energy saving potential of encouragement of VAV use in commercial area

	Reduction	**Reduction rate**
Fan power (OPU and ventilation fan)	302 [kWh]	7%
Thermal load of outdoor air (Cold water demand)	1,037 [GJ]	8%
Thermal load of outdoor air (Hot water demand)	2,693 [GJ]	16%

Table 5 shows a summary of the energy saving potential in the tenant side. “Encouragement of VAV use in commercial area” has the largest heat load reduction effect. There follows “Optimization of FCU and OPU in commercial area” and “Avoidance of hunting of FCU in commercial area”. The reduction rate of the heat demand for heating is large, because the total heat demand for heating is small in this building. Since one OPU supplies outdoor air to the rooms which is covered by multiple AHUs or FCUs, it should be noted that more detailed analysis for each tenant is required for more realistic estimation of energy saving potential of “Optimization of AHU and OPU in office area” and “Optimization of FCU and OPU in commercial area”.

Table 5. Summary of energy saving potential in tenant side

	Cooling heat demand (GJ)	**Heating heat demand (GJ)**	**Fan power consumptio n(kWh)**
Optimization of AHU and OPU in office area	531	531	0
Optimization of FCU and OPU in commercial area	779	779	0
Avoidance of hunting of FCU in commercial area	605	853	0
Encourage-ment of VAV use in commercial area	1037	2693	302
Total	2953	4856	302
Reduction rate*	2.1%	14.2%	0.3%

*Reduction rate is calculated based on total heat/electricity consumption in the building.

Simulation of heat source system and calibration

The simulation model for the heat source system was developed. A flowchart of the simulation is shown in Figure 6. This model consists of the following: chiller sequence control model, chiller COP model (function of part load ratio and cooling water temperature), boiler model and cooling tower model. The chiller COP model was first based on the manufacturer’s technical manual, but the rated COP was calibrated by the measured COP data, because individual differences were observed by data analysis. The detailed methodology is shown in Shimoda et. al., (2009). In the chiller sequence control model, constraints of both heat load and water flow rate are considered. The time step of this model is one hour. The input data for the simulation are hourly heat demand, water flow rate, and wet and dry bulb outdoor temperature measured in the building from April 2014 to March 2015. In this paper, energy consumption is expressed as primary energy consumption and the primary energy conversion

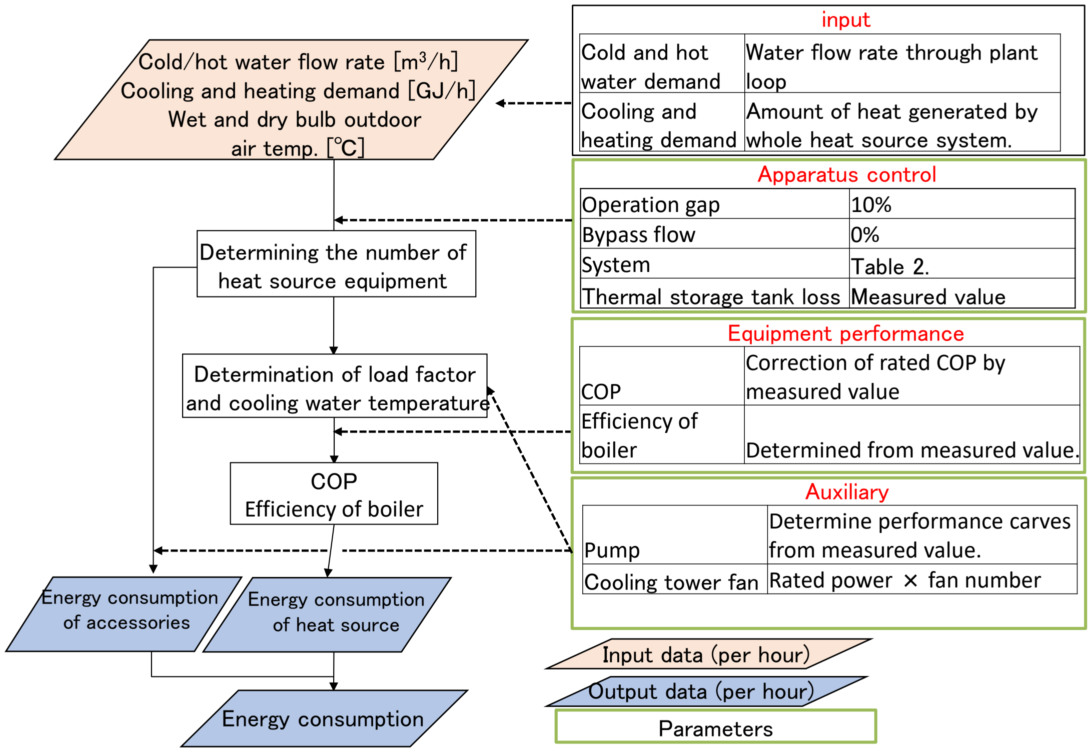

Figure 6. Flowchart of heat source system simulation

factors of electricity and city gas are set to 9.76 [MJ/kWh] and 45 [MJ/m^3], respectively.

By fixing the chiller control sequence to be the same as the measured sequence, the results of energy consumption are compared, as shown in Figure 7. The error of the annual total primary energy consumption is only 1.6%.

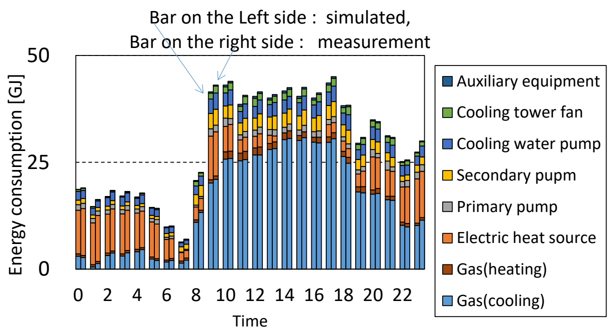

Figure 7. Comparison between simulated and measured energy consumption on 29th July, 2014

Energy saving potential of heat source system

Improvement of chiller sequence control

From the results of the simulation of the heat source system, it becomes clear that the change of the absorption chiller priority operation to an electricity-driven chiller priority operation increases total energy efficiency. The result of improvement in the chiller control sequence is shown in Figure 8.

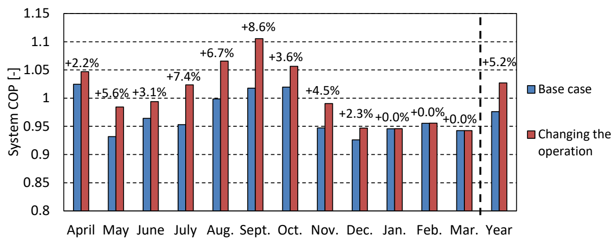

Figure 8. Change in COP of heat source plant by improving chiller sequence control

Optimization of cooling water temperature

Lowering the cooling water temperature by increasing the fan speed of cooling tower increases the COP of the chiller and reduces the energy consumption of the chiller. On the other hand, energy consumption of the fan is increased. Therefore, optimization of the cooling water temperature is required. The cooling towers in this building are 4 fans connecting electric chillers and 12 fans connecting absorption chillers, and the number of operating cooling towers is determined by the cooling water temperature. Figure 9 shows the cooling tower control procedure for the absorption chillers. In this study, cases of changing the cooling water temperature by -3°C/+3°C are examined. The results are shown in Table 6. The largest energy saving effect is 1.9% reduction in the -3°C case. In this case, energy consumption of the plant is decreased by 1.9%, although fan power consumption is increased by 41%.

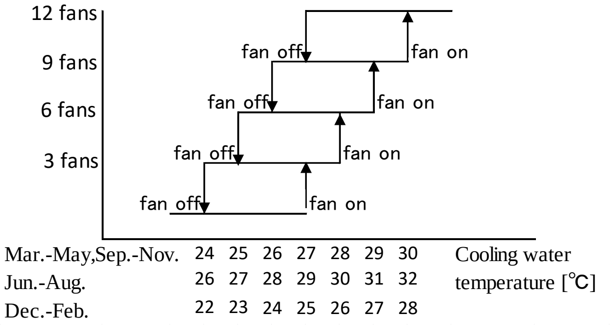

Figure 9. Cooling tower control procedure in base case (Absorption chillers)

Table 6. The result of sensitivity analysis on the cooling water temperature

	Electric chillers	Absorption chillers	Cooling tower fan	Total
+3°C	+7%	+2%	-25%	2.4%
+2°C	+5%	+1%	-18%	1.7%
+1°C	+3%	+1%	-10%	1.0%
Base case	0%	0%	0%	0.0%
-1°C	-3%	-1%	+13%	-0.8%
-2°C	-5%	-2%	+27%	-1.4%
-3°C	-7%	-2%	+41%	-1.9%

Effect of combination of energy saving measures

The actual energy saving effect by these measures must be evaluated by coupling the energy saving measures with a heat source system simulation since implementation of energy saving measures in the tenant side shown in Table 5 changes the heat demand profile. Table 7 shows the combinations of energy saving measures of each simulation case. The heat demand profile of each case is generated by calculating the effect of the hourly reduction of the heat demand of each tenant-side measure.

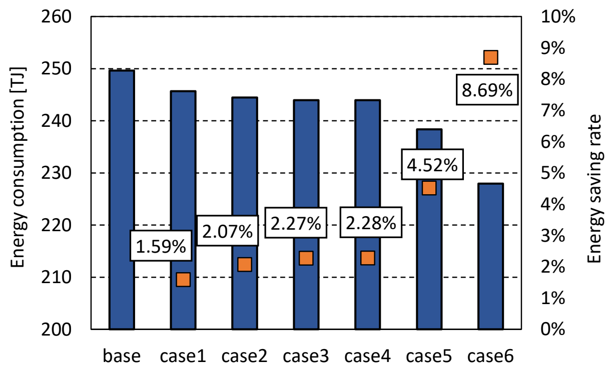

Figure 10. Energy saving effect by combination of tenant-side measures and heat source system optimization.

The simulation results of the total energy consumption of the whole building are shown in Figure 10. The energy saving effect of case 1 from the base case indicates the effect of optimization of the heat source system, and the differences of case 2–case 5 from case 1 indicate the total energy saving effect of each tenant-side measures.

In energy saving measures of the tenant side, use of the VAV in the commercial area is largest. Optimization of AHU and OPU in office area follows. Case 6 shows the energy saving potential when all tenant-side measures and heat source system measures are implemented. The primary energy consumption of Case 6 is reduced by 8.7% from the base case.

Figure 11 shows the system COP of the heat source plant. By optimizing heat source system operation, the system COP of the heat source plant is increased by 7.9%, and primary energy consumption of the whole building is reduced by 1.6%. The difference of COPs among case 1–case 6 indicates the effect of the heat demand profile change by the tenant-side measures. This effect is within 0.4%, as shown in Figure 11, and measures of the larger heat demand reduction effect further decrease the system COP, because the part-load operation hour is increased.

Table 7. Simulation cases of combination of tenant-side measures and heat source system measures

	Measures	Base	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Tenant side	Optimization of AHU and OPU in office area	×	×	○	×	×	×	○
	Optimization of FCU and OPU in commercial area	×	×	×	○	×	×	○
	Avoidance of hunting of FCU in commercial area	×	×	×	×	○	×	○
	Encouragement of use of VAV in commercial area	×	×	×	×	×	○	○
Heat source system	Change of the chillers' control sequence	×	○	○	○	○	○	○
	Change of cooling water temperature	×	○	○	○	○	○	○

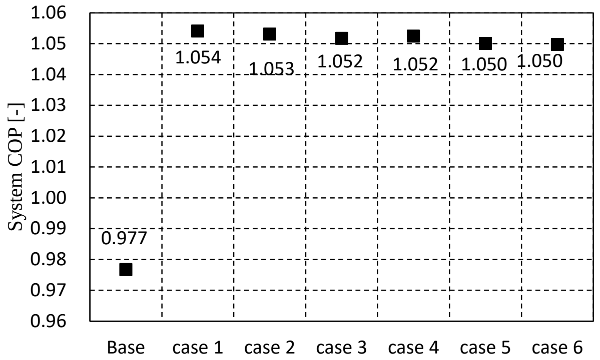

Figure 11. System COP of heat source plant

Conclusion

This paper presents case studies of energy saving potential search methods by analyzing large-scale energy and environmental data of a building with a quantitative evaluation method of the energy saving potential. The results are produced by coupling the data analysis and the building performance simulation.

The total energy saving potential of a large-scale complex building is 8.7%. It is noteworthy that this building is a new (i.e., no deterioration) building, in which cutting-edge energy efficient technologies are installed. Therefore, the number 8.7 % is considered to be the minimum potential of energy saving by installing the detailed data management system into the building and analyzing the data.

The effect of the combination of the energy saving potential estimation by data analysis and the heat source system simulation considering the heat load profile change is not significant in this case study. However, other kinds of energy saving measures in the tenant side may have the potential for significant change of the heat demand profile. For example, natural ventilation can reduce the cooling load, especially in low heat demand hours, such as night times and off-peak seasons. Under such conditions, this coupling method is expected to have a more significant advantage.

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