

METHODOLOGY FOR OPTIMIZING THE OPERATION OF HEATING/COOLING PLANTS WITH MULTI-HEAT SOURCE EQUIPMENTS USING SIMULATION

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ABSTRACT

A methodology for optimizing the operation of heating/cooling plants with multi-heat source equipments is proposed. The methodology decides the optimal combination of the running of multiple heat source equipments to minimize the energy consumption of a heating/cooling plant. The optimal running combination is decided automatically using MATLAB[®] Stateflow[®] tool corresponding to cooling and heating loads. The energy consumption at different running combination is simulated using MATLAB[®] Simulink[®] tool. A case study is introduced to demonstrate the methodology. An actual district heating/cooling plant located in Osaka Japan, which consist of two absorption chiller/heaters, one centrifugal chiller, one ice chiller, and two air-source heat pumps, is studied to find the optimal operation combination of the heat source equipments. The optimal running combination found by this method can reduce primary energy consumption by 19.7%, running cost by 12.8%, and carbon dioxide emission by 29.6%, compared to present operation.

KEYWORDS

Optimization, Energy consumption, Running cost, Heating/cooling plant, Running combination

INTRODUCTION

Energy and Environment are the most important issues in this new century. The comprehensive study on energy efficiency started since the Energy Crisis caused by the Middle East War in 1973 to 1974. The urgent need for oil security management and energy policy co-operation led to the establishment of International Energy Agency (IEA) (Scott 1994). In the field of building energy conservation, the idea that commissioning is a viable method to help ensure good performance of buildings and their Energy Conservation Measures (ECM) was gradually conceived since 1989, because some analyses on the data from the buildings participating in the energy conservation program revealed that many of the installed energy efficiency measures were not performing as expected (Bonneville Power Administration, 1992). Building commissioning is the process of ensuring that systems are designed, installed, functionally tested, and capable of being operated and maintained to perform in conformity with the design intent (ASHRAE, 1996).

The concept of commissioning is being gradually refined since its birth. Now commissioning is not only to verify whether building systems are in conformity with design intent, but also to verify and improve the design itself. Especially during operational phase, one of the main commissioning jobs is to optimize the operation of building systems. The optimization of heating/cooling plant, which is the heart and main energy consuming part, is considered to be so important that many researches have been conducted on the operation of heating/cooling plants. Celuch (2001) analyzed the issues of energy efficiency, cost, and operation on upgrading an actual central chiller water plant. Modeling of an actual cooling plant is also studied and the model is used for simulation and fault detection during the commissioning for a heating/cooling plant (Georges and Lebrun 2004). A program for power generation optimization is developed by SEGA (Anon). Zhang et al. (2000) used SEGA's Energy Optimization Program (EOP) to analyze the operation of a cogeneration power plant and found the optimal operation can save total costs by 10.4% compared to the original operation.

However, research on the method for optimizing the operational combination of heat source equipments in central heating/cooling plants for buildings can seldom be found. Corresponding to a requirement of heating/cooling, many different heating cooling source combinations can satisfy the requirement. It is necessary to select an optimal combination for the purpose of ensuring energy efficiency. However there are so many different combinations of multiple heating/cooling source equipments that it is difficult, even impossible, to check the performance of all the possible combinations experimentally on an actual plant. Therefore it is necessary to find a method to automatically check the performance of all possible combinations and determine the optimal combination. Simulation is considered to be a powerful tool to automatically check the performance of a building and its systems (Wang and Yoshida, 2003). This paper focuses on developing a method for determining optimal running combination of multiple heating/cooling equipments using simulation. For the purpose of validating the method proposed, then the method is applied to an actual district heating/cooling plant located in Osaka Japan, which consist of two absorption chiller/heaters, one centrifugal chiller, one

centrifugal ice chiller, and two air-source heat pumps, to find the optimal operational combination. Then the optimal operation is compared the original operation to check how much energy can be saved by the optimal operation.

OPTIMIZATION METHOD

Optimization problem

The objective of this optimization problem is to find the minimum value of an objective function, as shown in Equation 1.

$$\min \sum_{t=1}^N \sum_{n=1}^m O_{n,t} \tag{1}$$

The objective function should be the annual total energy consumption, running cost, or carbon dioxide emission related to all the equipments consuming energy in a heating/cooling plant.

The search space is the possible running combination of heating/cooling equipments, which can satisfy a certain heating/cooling requirement.

The objective function values are the sum of the time series values of all running machines. These time series values is difficult or impossible to obtain through conducting experiments on a real heating/cooling plant because annual data measurement takes too much time and there are too many possible running combinations to be studied. A quick and efficient way is to simulate the performance of all the possible running combinations to obtain these time series values.

Because the objective function is a discrete one, there is no mathematical solution for this optimization problem. The optimal solution can only be obtained by comparing the objective function values of all possible combinations and then find the optimal combination that gives minimum energy consumption, running cost, or carbon dioxide emission. The optimal solution might be different using different objectives, i.e. energy consumption, running cost, or carbon dioxide.

Ideal solution

Corresponding to a certain heating/cooling load and weather condition, an optimal solution should exist because different heating/cooling source equipments have different heating/cooling capacities and different efficiencies at different load factors. The optimal solution can be found though simulating the plant performance at all possible running combinations of the heating/cooling sources. Because all possible combinations are analyzed, the optimal solution is a theoretical and ideal solution.

For a plant with m heating/cooling source equipments, the number of all possible combinations is as shown in Equation 2.

$$\sum_{n=1}^m C_m^n = \sum_{n=1}^m \frac{m!}{n!(m-n)!} \tag{2}$$

For example, for the plant with three chillers, the number of all possible combinations is

$$\sum_{n=1}^3 C_3^n = C_3^1 + C_3^2 + C_3^3 = 7, \text{ as shown in Table 1.}$$

Among these running combinations, there might exist several different combinations can satisfy a same heating/cooling requirement. Through simulating the performance of a plant at these different combinations respectively and comparing the obtained objective function values, the optimal combination giving minimum objective value can be found out. For example, for a plant with three chillers, chiller 1, chiller 2, and chiller 3, the all possible combinations are shown in Figure 1, which is listed according to the order of load increasing. If chiller 2 has the same cooling capacity with chiller 3, the combination No. 2 and 3, No. 4 and 5 supply same cooling amount. If under a certain condition, for example during the hot and humid season, chiller 3 performs more efficiently than chiller 2, the optimal combination should be No. 3 instead of No. 2, No. 5 instead of No. 4. So the optimal combination should be as shown in Figure 2.

Table 1 Running combination of three chillers

Chiller 1	Chiller 2	Chiller 3	Combination No.
ON	ON	ON	1
		-	2
	-	ON	3
		-	4
-	ON	ON	5
		-	6
	-	ON	7

Practical solution

The former described solution is a theoretically ideal solution. For actual operation, for some reasons, such as chillers need time to boot up, it is not good to frequently start and stop a chiller in short time, etc., some ideal optimal combinations cannot be used. At most heating/cooling plants, the usually used operation strategy is to decide a priority order preliminarily. Then according to the order, heat source machines are started or stopped one by one correspond to load. The heat source equipment with the highest priority will be started firstly. When load increases and exceeds its capacity, the machine with secondly highest priority will be started. When load decreases to lower than a stop threshold, among the running machines the one with lowest priority will be stopped. All heat source machines are operated according to such logic.

For the former mentioned example plant with three chillers, chiller 1, chiller 2, and chiller 3, if the priority order for high to low is chiller 1 → chiller 2 → chiller 3, the combination of chiller 1, chiller 1 +

chiller 2, chiller 1 + chiller 2 + chiller 3 will be used accompanying to the load increasing from small to large, as shown in Figure 3 (A).

For this kind operation strategy, the optimal solution can be found through simulating the plant performance at all possible priority orders. For example, there are six possible priority orders for the example plant with three chillers, as show in the followings.

- A) Chiller 1 → Chiller 2 → Chiller 3
- B) Chiller 1 → Chiller 3 → Chiller 2
- C) Chiller 2 → Chiller 1 → Chiller 3
- D) Chiller 2 → Chiller 3 → Chiller 1
- E) Chiller 3 → Chiller 1 → Chiller 2
- F) Chiller 3 → Chiller 2 → Chiller 1

For these six priority orders, the running combinations corresponding to different loads are shown in Figure 3 from (A) to (F) respectively.

Through simulating the plant performance at the six priority orders, the priority order showing minimum objective function value is the optimal solution.

However, this optimal solution might not be the one that gives minimum object function value in the whole search field, but an optimal solution constrained by priority orders. For example, according to the ideal optimal solution shown in Figure 2, the optimal combination might be No. 1, 3 and 7 corresponding to small, middle, and large load. However, the combination of No.1, 3 and 7 cannot be

found in the combinations decided according to priority order, as shown in Figure 3. That is to say the practical optimal solution might not be the ultimate optimal solution. But this solution is practical for some operational reasons, such as chillers need time to boot up (generally half an hour), it is not good to start and stop chillers frequently, etc. the Ideal solution can give the minimum objective function value but might cause the frequently starting/stopping a heat source machine. The practical solution might not be the minimum one among all the possible combinations but the minimum one among the combinations excluding the ones that cause the frequently starting/stopping a heat source machine. Therefore in the following parts, the method for searching the practical optimal solution is analyzed.

SIMULATION METHOD

As mentioned in the former section, there is no mathematical solution for this optimization problem. The optimal solution can only be obtained by simulating the performance of a plant at all possible running combinations to find the optimal combination that gives minimum energy consumption, running cost, or carbon dioxide emission.

Simulating the performance of a plant mainly consists of two steps. Firstly, corresponding to the load at a time step, decide the on/off states of all the heat source equipments according to a certain running priority order. Secondly, simulate the performance of the running equipments to obtain

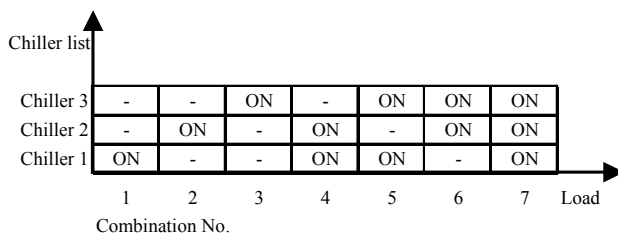


Figure 1 The combinations three chillers

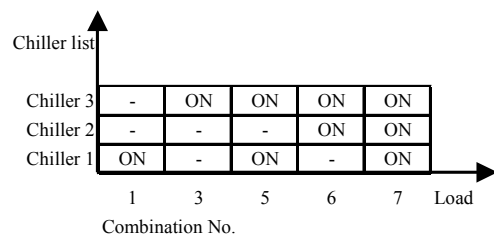


Figure 2 Ideal optimal solution of three chillers

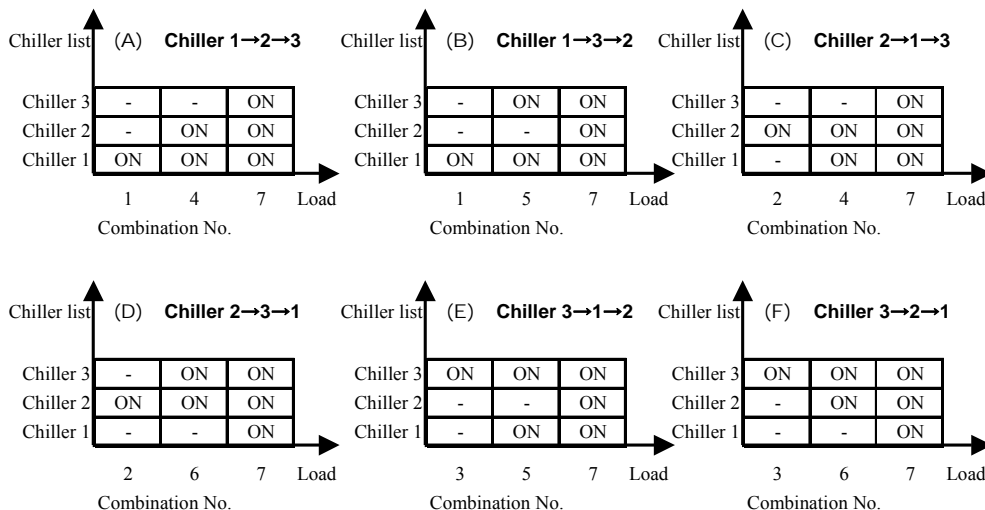


Figure 3 Practical optimal solution of a plant with three chillers

their energy consumptions, running costs, and carbon dioxide emission.

Operation mode determination

Here operation mode is defined as the on/off states of all the heating/cooling source equipments. For example, the combination No.5 shown in Figure 1 is called operation mode 5, whose on/off states are chiller 1 on, chiller 2 off, and chiller 3 on.

The on/off states of equipments are decided according to heating/cooling loads and start/stop thresholds decided using the heating/cooling capacities of these equipments, as shown in Figure 4. When the load exceeds a load threshold L_{i2} , which is the capacity of chiller 1, one more chiller, chiller 2, will start to satisfy the load requirement. When load decrease to lower than the load threshold L_{d1} , which is $n\%$ ($\leq 100\%$) of the capacity of chiller 1, chiller 2 will stop. With such logic, the operation mode, i.e. the running combination of heat source equipments, can be determined.

A general operation mode determination flow is described in Figure 5 for the plants with thermal storage system and supplying both hot and chilled water.

Plant performance simulation

Which machine is running at a certain time step can be decided using the method explained at the former section. Next is to simulate the performance of the running machines.

Before simulate machine performance, it is necessary to make mathematical models of all the machines. It can be a physical model or regression model fitted using its specification data. Regression models are often used because the heat source machines specification data or performance curves are usually easy to obtain and regression models can have enough simulation accuracy. For simulating plant performance, generally the following equipment models are necessary.

- Chiller (include heat pump)
- Boiler
- Pump
- Cooling/heating tower
- Thermal storage tank
- Heat exchanger
- Header

As an example, the modeling of a chiller is explained. Firstly obtain the chiller specification data or performance curve

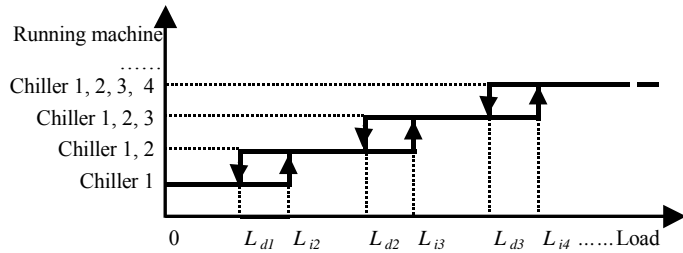


Figure 4 Determine running equipments according to load

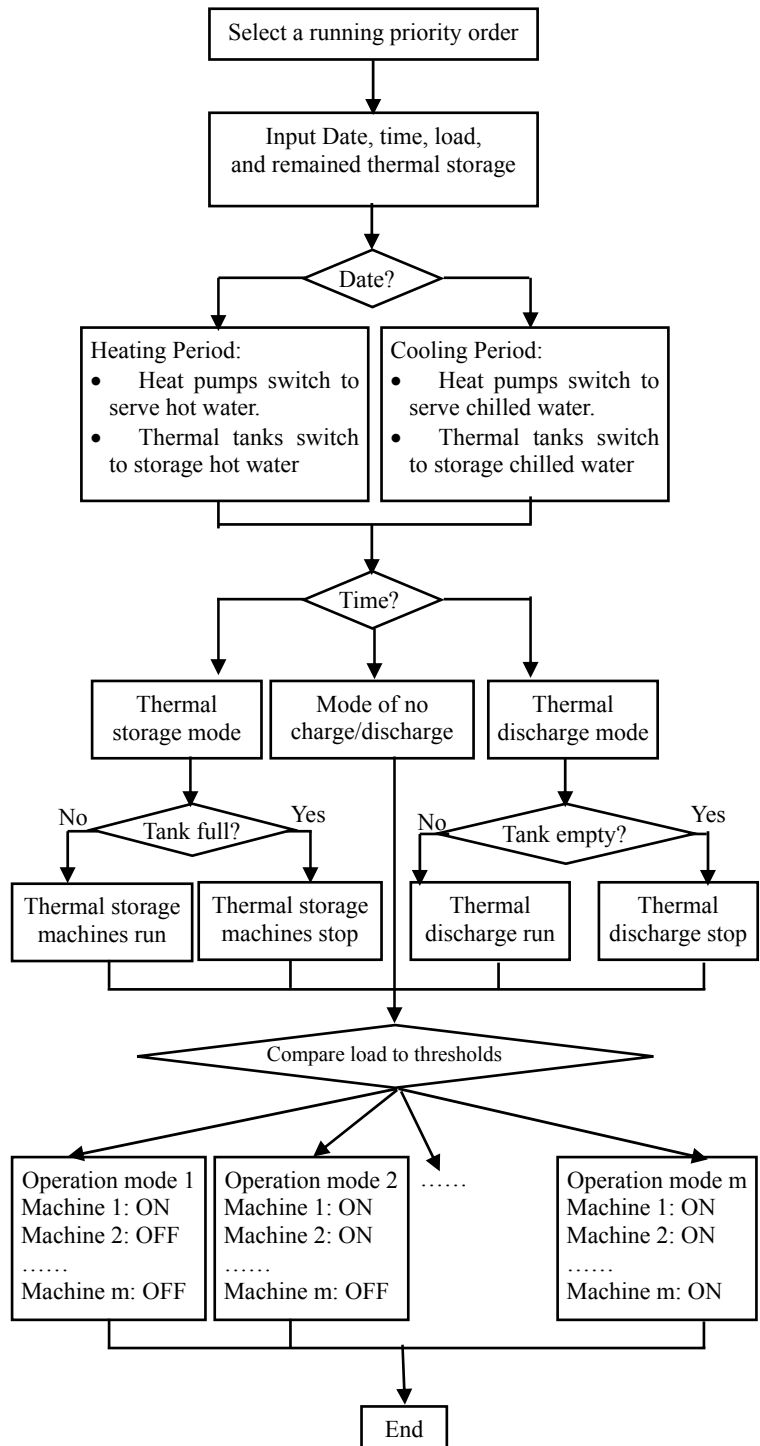


Figure 5 Flow chart for operation mode determination

from manufactures. An example chiller's performance curve is shown in Figure 6. Then use the specification data to fit the coefficients in the chiller regression model, as shown in Equation 3 to 9.

$$r_E = (a_1 r_Q^2 + a_2 r_Q + 1)(a_3 r_{T_{eo}}^2 + a_4 r_{T_{eo}} + 1) (a_5 r_{T_{cin}}^2 + a_6 r_{T_{cin}} + 1)(a_7 r_{M_e}^2 + a_8 r_{M_e} + 1) (a_9 r_{M_c}^2 + a_{10} r_{M_c} + 1) \quad (3)$$

$$r_E = \frac{E}{E_{rate}} \quad (4)$$

$$r_Q = \frac{Q - Q_{rate}}{Q_{rate}} \quad (5)$$

$$r_{T_{eo}} = \frac{T_{eo} - T_{eo,rate}}{T_{cin,rate} - T_{ein,rate}} \quad (6)$$

$$r_{T_{cin}} = \frac{T_{cin} - T_{cin,rate}}{T_{cin,rate} - T_{ein,rate}} \quad (7)$$

$$r_{M_e} = \frac{M_e - M_{e,rate}}{M_{e,rate}} \quad (8)$$

$$r_{M_c} = \frac{M_c - M_{c,rate}}{M_{c,rate}} \quad (9)$$

As shown in Equation 3, the chiller energy consumption rate r_E is calculate using five dimensionless variables, cooling production r_Q , chilled water outlet temperature $r_{T_{eo}}$, cooling water inlet temperature $r_{T_{cin}}$, chilled water flow rate r_{M_e} , cooling water flow rate r_{M_c} . If a chiller's performance curves related to the five variables are not all available, for the unavailable variables the rated values have to be used. When rated values are used, the term related to that variable will be equal to one so that in Equation 3 the terms with the unavailable variables will disappear. For example, to the chiller performance curve shown in Figure 6, only cooling production r_Q and cooling water inlet temperature $r_{T_{cin}}$ are available.

So the term of $r_{T_{eo}}$, r_{M_e} , and r_{M_c} disappeared and the chiller model becomes a formula as shown in Equation 10.

$$r_E = (a_1 r_Q^2 + a_2 r_Q + 1)(a_3 r_{T_{cin}}^2 + a_4 r_{T_{cin}} + 1) \quad (10)$$

The fitted coefficients are as follows.

$$a_1 = 0.1154, a_2 = 0.9325, a_3 = 0.1958, a_4 = 0.3527$$

In order to check the model accuracy, the correlation between model calculated data and specification data is shown in Figure 7. The relative error is 0.25% and Root Mean Square Error (RMSE) is 1.2%, which shows that the

regression model is accurate enough to use it for simulating the chiller's performance.

Simulation tool

For the former mentioned two simulation steps, operation mode determination and plant performance simulation, MATLAB® Stateflow® and Simulink® are considered to be convenient tools to building simulation model, conduct simulation and visualize simulation results. Stateflow can visualize the operation mode determination flow shown in Figure 5. During simulation, the operation mode determination flow is visualized by highlighting the state be selected. As shown in Figure 8, the branch highlighted with thick line is the combination being selected according to priority order and current load.

Using Simulink, all equipment and component models can be connected to construct the whole heat source system model and then to conduct simulation and visualize the simulation results. An example Simulink model of a cooling/heating plant is shown in Figure 9.

In order to validate the optimization method proposed by this paper, the following section describes the optimization for an actual cooling/heating plant.

CASE STUDY

A cooling/heating plant located in Osaka Japan is used for this case study. The profile of the

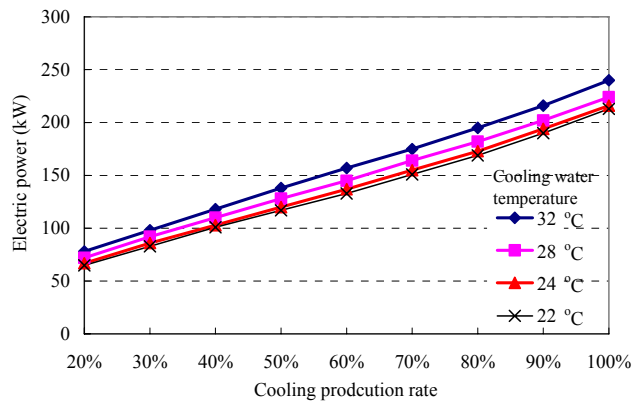


Figure 6 Performance curve of an example chiller

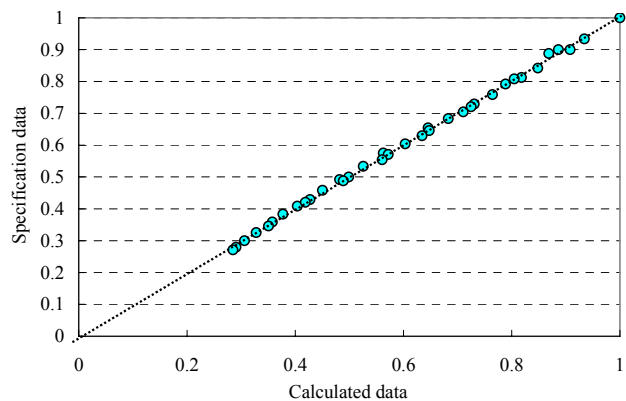


Figure 7 Regression model accuracy

cooling/heating plant is shown in Table 2. It consists of two gas-fired absorption chiller/heaters GAR-1 and GAR-2, two air source heat pumps RHP-3 and RHP-4, one centrifugal chiller TBR-5, and one ice chiller TBR-6, which makes ice using super-cooled water.

The present operational priority order is shown in Table 3. During daytime, the gas-fired absorption chillers take priority to run over other heat source machines. While during nighttime, because of lower electricity price (roughly half of daytime price) the centrifugal chiller takes priority.

The operation mode determination is automated and visualized using Stateflow. Then the on/off states of all equipments decided by Stateflow are inputted to the Simulink model of the plant to simulate the plant performance. The outputs are energy consumption, chilled water supply temperature, thermal amount in ice tank.

Table 2 Profile of an example heating/cooling plant

Heat source machines	Name	Capacity (kW)	Number
Gas-fired absorption chiller/heater	GAR-1	1759	1
	GAR-2		1
Air source heat pump	RHP-3	339	1
	RHP-4		1
Centrifugal chiller	TBR-5	1406	1
Ice-making chiller (Ice making mode)	TBR-6	703.2	1
Ice-making chiller (Chilled water mode)		879	

Table-3 Present operation priority order

	Daytime	Nighttime
1	Thermal discharge	TBR-6 (Ice-making mode)
2	GAR-1	TBR-5
3	GAR-2	RHP-3
4	TBR-5	RHP-4
5	RHP-3	GAR-1
6	RHP-4	GAR-2
7	TBR-6 (Chilled water mode)	-

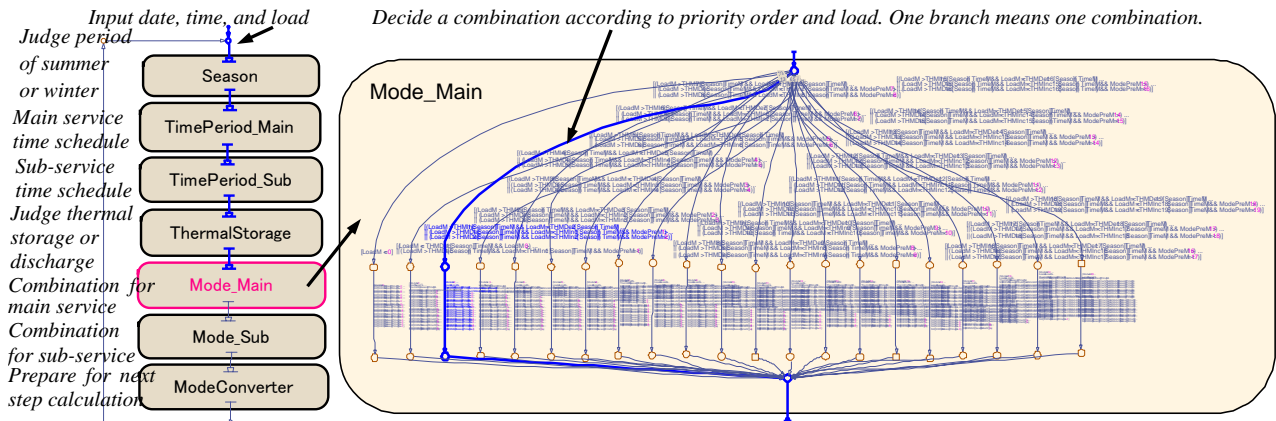


Figure 8 Visualized operation mode determination

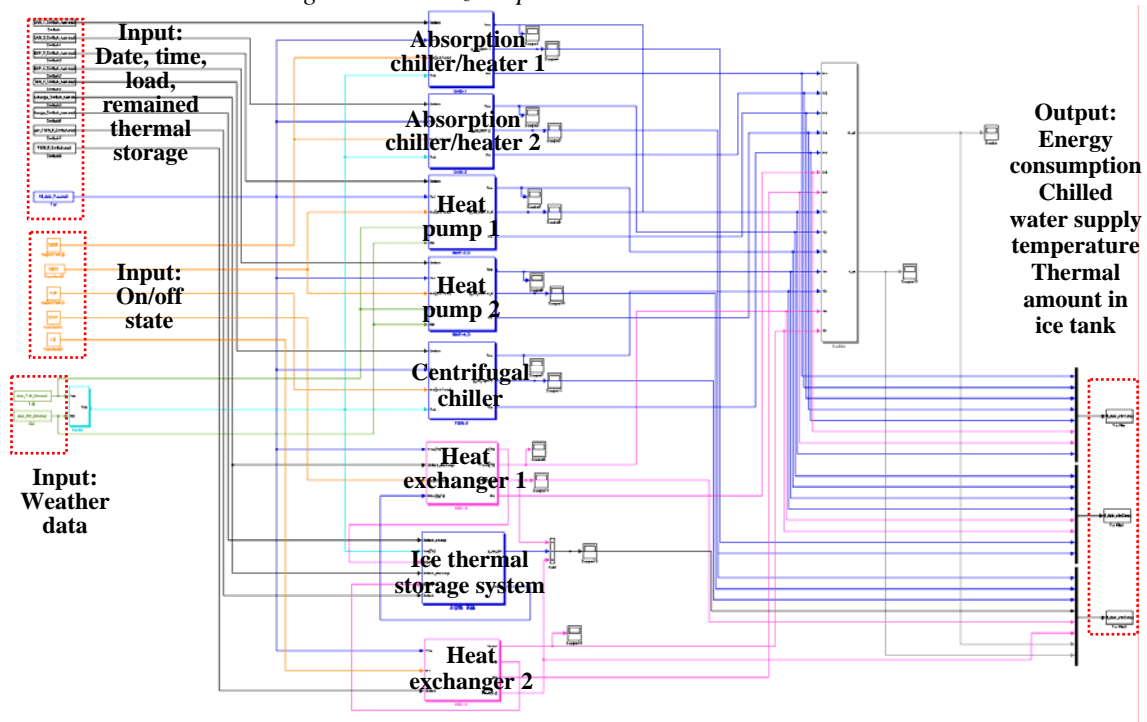


Figure 9 An example Simulink model of a cooling/heating plant

The running cost and carbon dioxide emission are calculated through multiplying the energy consumption obtained from simulation by energy price and carbon dioxide emission per unit energy, as shown in Equation 11 to 14. The prices used for energy cost and carbon dioxide emission are listed in Table 4.

$$C_{el} = P_{bel}(1.85 - \cos\phi)EC + P_{ael}EL - P_sEL_s \quad (11)$$

$$C_g = GC + P_{bg}GR + P_{ag}G \quad (12)$$

$$CD_{el} = CU_{dt}EL_{dt} + CU_{nt}EL_{nt} \quad (13)$$

$$CD_g = CU_gG \quad (14)$$

For the purpose of saving time, not all possible priority orders are analyzed. According to authors' understanding, six series of priority order are selected for simulation, as shown in Table 5. Case 1 to 4 are used to check the plant performance if only daytime priority order is changed. Case 1 and 2 are used to check how the plant performance changes if electric heat source machines take priority over gas-fired machines during daytime. Case 3 is used to check the performance if air source heat pumps take priority over the centrifugal chiller. Case 4 is used to check the performance without thermal storage. Case 5 and 6 are used to check the performance changes caused by only changing the nighttime priority order. Case 5 lets air source heat pumps and Case 6 lets gas-fired absorption chiller take priority during nighttime.

Because not all the possible combinations are simulated, the solution might not be the optimal solution. But compared to present operation, if change daytime priority order to that used in case 1 and change the nighttime priority order to that used in case 5, the primary energy consumption can be reduced by 19.7%, running cost can be reduced by 12.8%, and carbon dioxide emission can be reduced by 29.6%, as shown in Figure 10. This result shows that for the plant discussed, the centrifugal chiller consumes fewer energy and cost than the gas-fired absorption chiller. During nighttime, running the air-source heat pumps instead of the centrifugal chiller can save energy and cost.

CONCLUSION

This paper proposes a methodology for optimizing the operation of heating/cooling plants with multiple heat source equipments. Simulation is used to solve the optimal problem. Simulation tools of MATLAB Stateflow and Simulink are used to conduct the simulation and visualize the results. A case study is introduced to validate the optimization method. The best combination found using the method can reduce primary energy consumption by 19.7%, running cost by 12.8%, and carbon dioxide emission by 29.6%, compared to present operation mode.

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NOMENCLATURE

$a_1, a_2, a_3, \dots, a_{10}$ – Fitted coefficients

E – Energy consumption, (kW)

EC – Electricity contract capacity, (kVA)

EL – Sum of electricity consumption, (kWh)

C – Running cost, (yen)

CD – Carbon dioxide emission, (kg)

CU – Carbon dioxide emission per unit energy, (kg/kWh for electricity, kg/Nm³ for gas)

G – Sum of gas consumption (Nm³)

GR – Rated gas consumption (Nm³/h)

GC – Gas contract price (yen/contract)

L – Load threshold for starting or stopping a machine

m – The total number of heat source equipment

M – Flow rate, (kg/s)

n – Heat source equipment number

N – Period of time series objective values to be summed up

O – Objective to be minimized

P – Price, (yen per unit energy)

Q – Load, (kW)

r – Ratio

T – Temperature, (°C)

$\cos\phi$ – Power factor

Subscriptions

a – Amount of energy consumption

b – Energy base price decided according to contract capacity

c – Cooling water

d – Decrease running machine number (to stop a machine) *rate* – rated value
dt – Daytime *s* – Thermal storage
e – Chilled water *t* – Time step
el – Electricity
g – Gas
i – Increase running machine number (to start a machine)
in – Inlet

Table 4 Energy price and carbon dioxide emission per unit energy

	Energy price				Carbon dioxide discharge		
	Contract price		Retail price			kg/kWh	
Electricity	yen/kVA	US\$/kVA		yen/kWh	US\$/kWh	Daytime	0.293
	¥ 1,648.50	\$ 14.00	Summer	¥ 10.02	\$ 0.085		
			Except for summer	¥ 9.10	\$ 0.077	Nighttime	0.266
			Subtract for thermal storage	¥ 4.90	\$ 0.04		
Gas	yen/contract	US\$/contract		yen/Nm ³	US\$/Nm ³	kg/m ³	
	¥ 75,600.00	\$ 641.82	Summer	¥ 41.92	\$ 0.36	2.29	
	Price on rated consumption		Winter	¥ 46.03	\$ 0.39		
		yen/(Nm ³ /h)	US\$/Nm ³ /h				
	Summer	¥ 945.00	\$ 8.02				
	Winter	¥ 2,258.00	\$ 19.17				

1 US\$ = 117.79 yen

Table 5 Cases used for optimization

		Present	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Daytime	1	Thermal discharge	Thermal discharge	Thermal discharge	Thermal discharge	GAR-1	Same as present priority order	
	2	GAR-1	TBR-5	RHP-3	GAR-1	GAR-2		
	3	GAR-2	GAR-1	RHP-4	GAR-2	TRB-5		
	4	TBR-5	GAR-2	GAR-1	RHP-3	RHP-3		
	5	RHP-3	RHP-3	GAR-2	RHP-4	RHP-4		
	6	RHP-4	RHP-4	TBR-5	TBR-5	TBR-6 (Chilled water mode)		
	7	TBR-6 (Chilled water mode)	TBR-6 (Chilled water mode)	TBR-6 (Chilled water mode)	TBR-6 (Chilled water mode)	-		
Nighttime	1	TBR-5	Same as present priority order				RHP-3	GAR-1
	2	RHP-3					RHP-4	GAR-2
	3	RHP-4					TBR-5	RHP-3
	4	GAR-1					GAR-1	RHP-4
	5	GAR-2					GAR-2	TBR-5
		TBR-6 (Ice making mode)					TBR-6 (Ice making mode)	TBR-6 (Ice making mode)

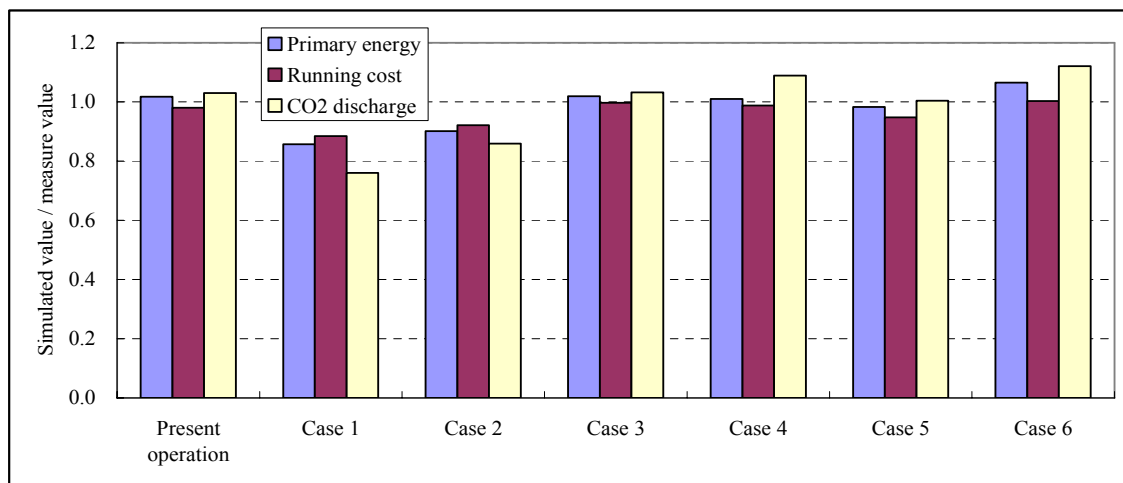


Figure 10 Comparison of energy consumption, running cost, and CO₂ emission

n – Heat source equipment number
nt – Nighttime
o – Outlet