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OPERATION PLANNING OF URBAN DISTRICT HEATING AND COOLING PLANTS CONSIDERING THE CONTINUOUSNESS OF LOAD AND DRIVING

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Abstract. In previous studies on operation planning of urban district heating and cooling plants, plans for operating the instruments are formed on one hour basis. However, it is important to consider operation planning by the smaller unit of time since the load on the plants rapidly increases in the morning. On the other hand, if the unit of time for planning is too small, the computational time for obtaining operation plans becomes huge due to the increase of the number of input data for prediction and the combinatorial number of plans available. Furthermore, it is needed to take account of the cost and time of switching instruments in order to derive more practical operation plans. In this paper, we propose a heat load forecasting method in which the number of input data does not explosively increase even when more detailed plans are made. And we propose several operation planning models based on various criteria and examine the efficiency of the proposed models through the comparison of the experimental results using actual data.

1 Introduction Recently in the city, for the energy efficiency use, for the maintenance of environment and for the prevention of urban disaster, the urban district heating and cooling system introduction case increases. Pattern diagrams of the urban district heating and cooling system are shown in Fig. 1. The urban district heating and cooling system is a system which intensively produces cold water and the steam, etc. used for the air conditioning in a certain region, and supply them circulatory through the pipeline to facilities in the region. There are heat source equipments such as large-scale freezers and boilers in the system. So, for efficient operation of the system, it is preferable to decide the best operation pattern of the heat source based on the heat-load prediction, to consider the risetime of the heat source equipments, and to operate the system without uselessness. Therefore, as the technology that supports a highly effective operating of the system, the heat-load prediction technique is being researched [4, 5, 6, 7]. And the best operation plan technique of the heat source equipment based on the prediction is being researched [1, 4, 2, 6]. These treat the optimization problem of the operating plan every one hour. But in the real system, the system has to be operated according to a rapid load change in the morning. So, a more detailed plan is necessary in the real system. To make a more detailed plan, the past technique [2, 6] need long processing time because the number of combinations of possible plan increases. So, it is not practicable. In addition, to schedule a more realistic operating plan, it is necessary to consider cost and the equipment risetime.

In this paper, we proposes the prediction procedure of the heat-load demand to which the processing time does not increase by subdividing the unit time of the plan, we proposes some operation planning model based on various ideas that consider cost and the equipment risetime, and we compare and examine the utility of the proposed model through the simulation experiment that uses real data.

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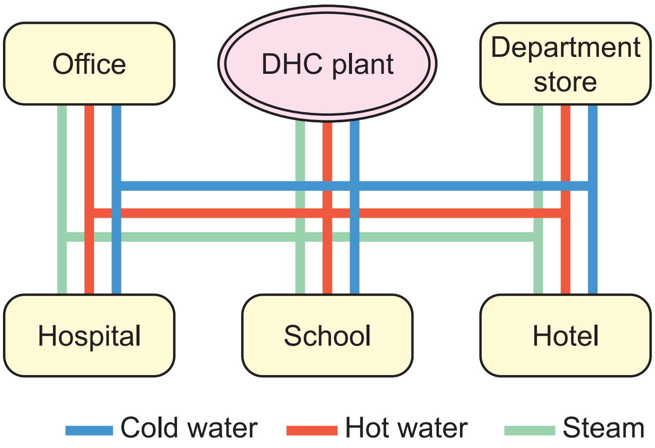

Figure 1: Urban district heating and cooling plants

2 Heat-load prediction The amount of steam and cold water that the region needs is called heat-load in this paper. In the urban district heating and cooling plant, as the absorbing freezer generates cold water by using the steam that is generated by the boiler, heat transfer medium's requirement are interdependent.The predictive value of all heat-loads that the system supplies to the region is needed for the optimization of the operating plan. Here, the prediction procedure is described by explaining an example of three kinds of demand for the calorie of cold water, the flowing quantity of cold water, and the flowing quantity of steam. The relation between the heat-load and the normal temperature during a day (except weekend and national holiday) of the urban district heating and cooling plant in the Kanto region in 2009 of the weekend is shown in Fig. 2. It is understood that the heat-load is greatly influenced from the weather condition, and the heat-load and the normal temperature are correlated nonlinearly as shown in Fig. 2. Next, the transition of one week of the heat-load and the temperature are shown in Fig. 3. It is understood that each heat-load has the periodicity every day as shown in Fig. 3, and the aspect is different between the weekend and the rest. Moreover, It is understood that the amplitude of the pattern of the cyclic variation is almost constant and has not been influenced so much from the change in the amplitude of the air temperature variation. Based on this result, it will predict the heat-load of a day by predicting the total on the day and the change pattern of the day of the heat-load separately, and dividing the total heat-load on the day in proportion in the pattern of the day of the heat-load. The heat-load of a day is classified in the case of weekday and in the case of holiday, it models by the multiple regression analysis of which the explanatory variable are weather information and recent results, and it is predicted by applying the weather forecast values of the day to the model. However, the explanatory variable used for the multiple regression uses the regional predictive values announced by the Meteorological Agency such as normal temperature, the highest temperature, the lowest temperature, and the relative humidity, to express a nonlinear tendency as shown in Fig. 2, the square paragraph of the normal temperature and the absolute humidity calculated from humidity and normal temperature are added to the explanatory variable, and the explanatory variable is optimized by using step wise method [3]. The explanatory variable adopted for the prediction of each heat-load is shown in Table 1. As shown in Table 2, the relation between predictive values and results of the relative humidity and absolute humidity are not intercept$\fallingdotseq 0$ and slope$\fallingdotseq 1$. So, there are some bias in the predictive values of them.

The reason to use the predictive values of the relative humidity and absolute humidity, instead of the results of them, as the explanatory variable for modeling is to consider the factor of relation between predictive values and results of the relative humidity and absolute humidity. Results in the pattern of demand during a day ware made by dividing the demand results by the mean value on the day, and the predictive value was assumed to be a mean value of the same day of the week in the last several weeks. The results of the prediction is shown in Fig. 4. This results is made by dividing the heat-load predictive values of the day in proportion in the same pattern of a day of the week, after the heat-load of the day is predicted from the weather forecast values and results by the multiple regression. Because of the error of the weather forecast and the model, there are some cases that the peak of heat-load is different between prediction and results. But overall, this result shows that the heat-load predictive values close to its results can be predicted by this procedure.

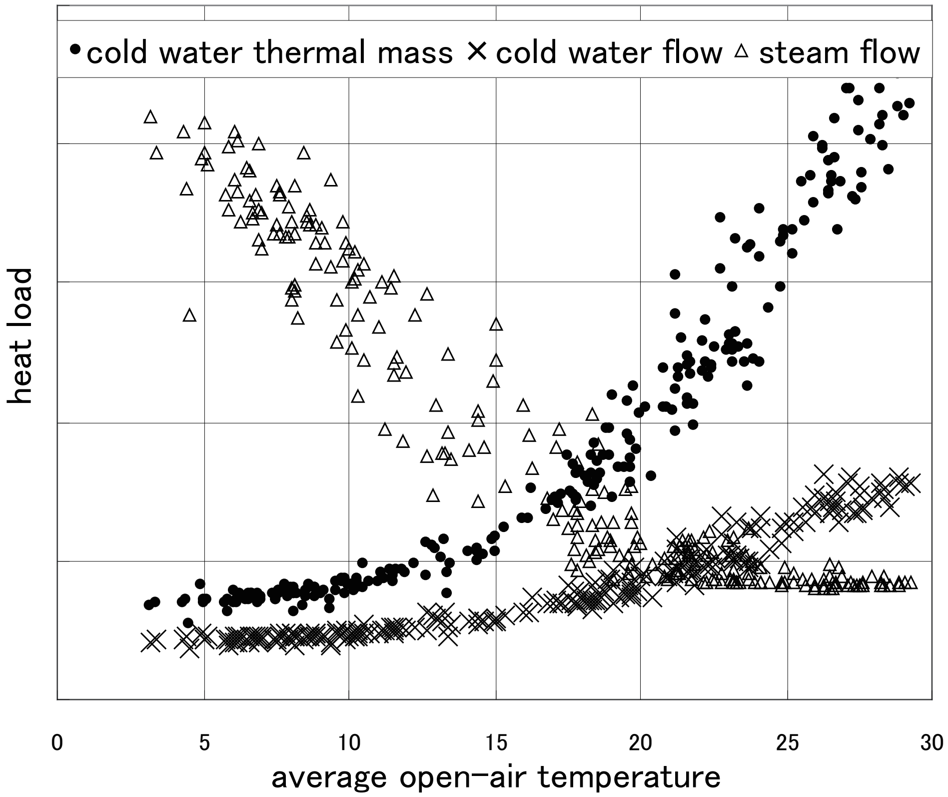

Figure 2: Correlation graph of heat-load and normal temperature (1/1-12/31)

3 Target system of the operation planning Next, it considers optimization of the operation plan by the heat-load predictive values. In this paper, the data of an actual urban district heating and cooling plant is used to judge whether the operation plan planned by optimization is realistic. Pattern diagrams of the actual plant is shown in Fig. 5. This plant is composed of 4 boilers, 10 absorbing freezers, and 2 cogeneration systems and their incidental equipment. All of the boiler of this plant generates the high-pressure steams, and steam for a regional supply is made by Decompression. Nine freezers generate cold

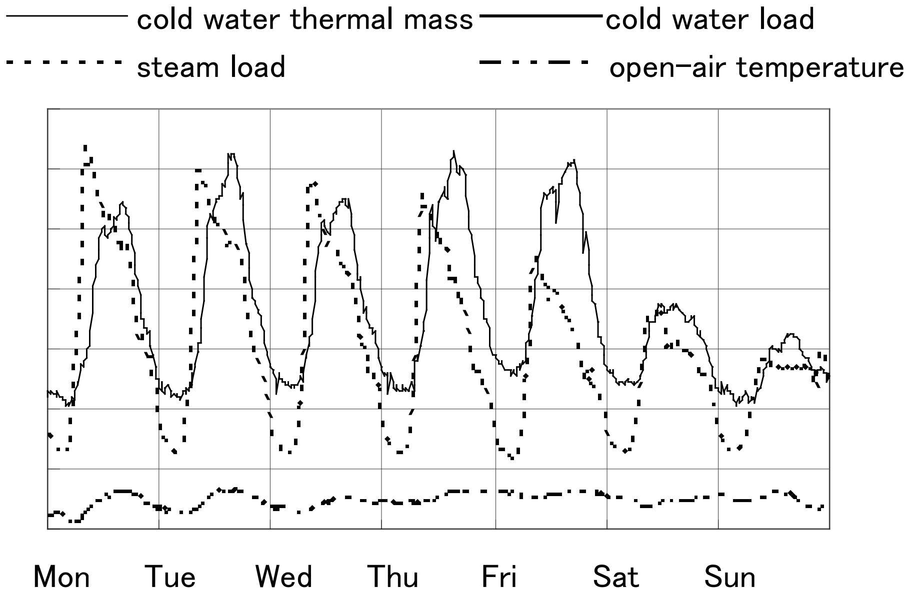

Figure 3: Heat-load transition of one week (1/26-2/1)

Table 1: The results of optimization of explanatory variables for heat-load prediction

	Cold water calorie	Cold water flow	Steam flow
Intercept	O	O	O
Highest temperature		O	
Lowest temperature			
Normal temperature	O	O	O
(Normal temperature)^2	O	O	O
Relative humidity	O	O	O
Absolute Humidity	O	O	O
Recent results		O	O
R^2	0.9681	0.9696	0.9815

Table 2: The relation between the weather forecast values and results

	Average temperature	Highest temperature	Lowest temperature	Relative humidity	Absolute humidity
Intercept	0.04	0.30	0.13	-4.18	-0.13
Gradient	1.00	1.00	0.99	0.91	0.87
R^2	0.98	0.95	0.97	0.72	0.96

water by using the high-pressure steam. Two freezers ’ used steam is recycled as steam for the region. One cogeneration system is the power supply to the customer and it generates steam for a regional supply. Another cogeneration system is for this plant and it generates the high-pressure steam. In contract with electric power company, supply electric power to the electric power company is prohibited. So, both of the cogeneration system generate the

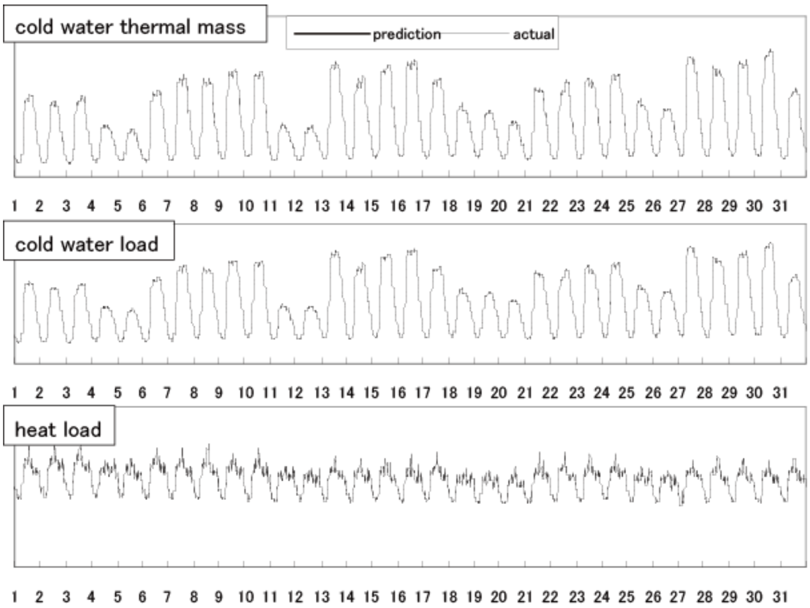

Figure 4: The result of prediction of heat-load (7/1-7/31)

electric power within the range to supply a demand.

4 Formulation of Operation planning Given the predicted cold water calorie demand $L_r(t)$, the predicted cold water flowing quantity $L_{fr}(t)$, the predicted steam flowing quantity $L_s(t)$, and the electric energy forecast value for region $L_e(t)$ at time $t(t = 1, 2, \ldots,$ under the operation condition immediately before, the operation planning problem of the plant can be modeled as the cost minimization problem that the optimization object (decision variable) are the running condition (of every time of unit of a day) of freezers$(r_1, r_2, \ldots, r_{10})$, boilers$(b_1, b_2, \ldots, b_4)$ and cogeneration systems(G_1,G_2).

5 Possible combination of running equipment and modeling of cost First, a possible freezers running combination is that the load rate of all freezers' output cold water calorie

$$R_r(t) = \frac{L_r(t)}{\sum_{i=1}^{10} \delta r_i(t) \cdot M_{r_i}} \tag{1}$$

and the load rate of all freezers ' output cold water flowing quantity ,

$$R_{fr}(t) = \frac{L_{fr}(t)}{\sum_{i=1}^{10} \delta r_i(t) \cdot M_{fr_i}} \tag{2}$$

meet the following requirements for each freezers.

$$\delta r_i(t) \cdot R_{r_i}^{\min} \leq R_r(t) \leq 1 - Y_r \tag{3}$$

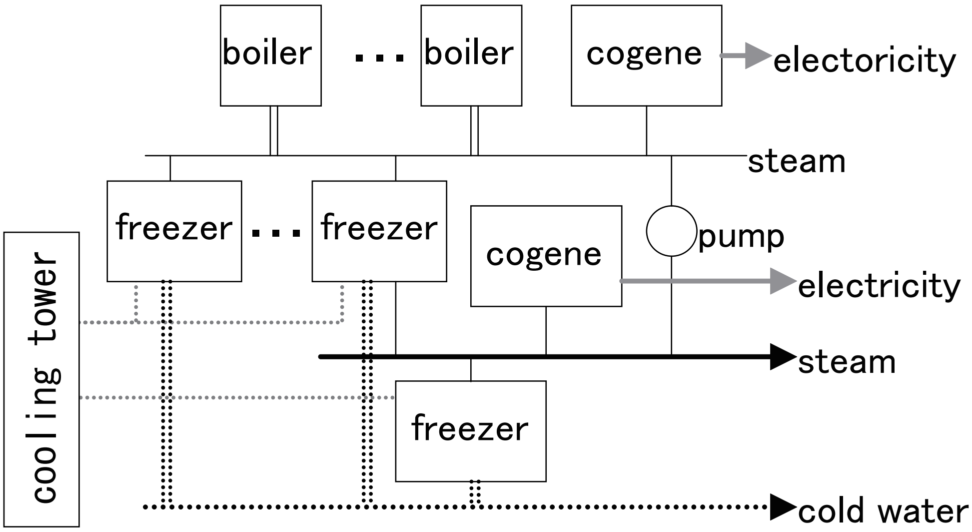

Figure 5: Block diagram of the actual urban district heating and cooling plant

$$\delta r_i(t) \cdot R_{fr_i}^{\min} \leq R_{fr}(t) \leq 1 - Y_{fr} \tag{4}$$

where $\delta r_i(t)$ is the freezers running combination (it is a value at time t that become 1 when freezer r_i is running and otherwise become 0), M_{r_i} and M_{fr_i} are each the capacity of output cold water calorie of freezer r_i and the capacity of output cold water flowing quantity of freezer r_i, $R_{r_i}^{\min}$ and R_{fr_i} are similarly the lowest load rate of freezer r_i, and Y_r and Y_{fr} are safety margins to maintain the quality of cold water to the heat load change. When the running combination of the freezers is decided, the steam consumption of the freezers $S_r(t)$ and the amount of power consumption of the freezer $E_r(t)$ are calculated respectively by the following expression.

$$S_r(t) = \sum_{i=1}^{10} \delta r_i(t) \cdot F_{r_i}(R_r(t)) \tag{5}$$

$$E_r(t) = \sum_{i=1}^{10} \delta r_i(t) \cdot F_{er_i}(R_r(t)) \tag{6}$$

where $F_{r_i}(R_R(t))$ and $F_{er_i}(R_r(t))$ are the steam consumption and the amount of power consumption of freezer r_i in the condition that load rate is $R_r(t)$. These are functions that identified from results. In addition, because the equipment of the cooling system that composes the freezer is driven automatically, those amounts of power consumption E_{fun} is calculated by the following expression.

$$E_{fun}(t) = F_{fun}(L_r(t)) \tag{7}$$

where, $F_{fun}(L_r(t))$ is a function of the calorie demand of cold water and the weather condition, and F_{fun} is identified from results. The amount of power generation of the cogeneration system G_1 for the region is shown as follows.

$$E_{G_1}(t) = \min(L_e(t) + H_{G_1} - K_{G_1}, M_{G_1}) \tag{8}$$

where K_{G_1} is the constant to prevent electricity from flowing backward, M_{G_1} is the power generation ratings capacity of the cogeneration system G_1, and H_{G_1} is amount of power consumption of accessory. In that case, the amount of the generation steam $S_{G_1}(t)$ of the cogeneration system G_1 is shown as follows.

$$S_{G_1}(t) = F_{G_1}(E_{G_1}(t)) \tag{9}$$

where $F_{G_1}(E_{G_1}(t))$ is a function of the amount of power generation of the cogeneration system G_1, and F_{G_1} is identified from results. Amount$E_b(t)$ of power consumption of the running boilers is defined as

$$E_b(t) = \sum_{i=1}^{4} \delta_{b_i}(t) \cdot F_{eb_i}(R_b(t)) \tag{10}$$

where $\delta_{b_i}(t)$ is the boilers running combination (it is a value at time t that become 1 when boiler b_i is running and otherwise become 0), $F_{eb_i}(R_b(t))$ is a function to model the amount of power consumption of boiler b_i by the load factor, and $R_b(t)$ is the output load rate of boiler $b_i.R_b(t)$ is shown as follows.

$$R_b(t) = \frac{S_b(t)}{hp\sum_{i=1}^{4} \delta b_i(t) \cdot M_{b_i}} \tag{11}$$

where hp is the increasing rate of the steam when the steam for region is made from high-pressure steam by through the reducing valve, M_{b_i} is the capacity of output steam of the boiler b_i, and $S_b(t)$ is the amount of the generation steam of running boilers. $S_b(t)$ is shown as follows.

$$S_b(t) = S_r(t) + (1 + K_t)L_s(t) - S_{G_1}(t) - S_{G_2}(t) \tag{12}$$

where K_t is the constant that shows the effect of deaeratares, and $S_{G_2}(t)$ is the amount of the generation steam of the cogeneration system G_2.

Therefore, the amount of power consumption of the entire plant is shown as follows.

$$E(t) = E_0 + E_{fun}(t) + E_r(t) + E_b(t) + \delta_{G_2}(t)F_{e_{G_2}}(R_{G_2}(t)) \tag{13}$$

where E_0 is an electric energy necessary for the plant operation excluding the heat source equipment, $\delta_{G_2}(t)$ is the value at time t that become 1 when cogeneration system G_2 is running and otherwise become 0, and $F_{e_{G_2}}(R_{G_2}(t))$ is a function to model the amount of power consumption of the cogeneration system G_2 by the cogeneration system's load rate. The amount of power generation of G_2 is shown as follows.

$$E_{G_2}(t) = \delta_{G_2}(t)\min(E(t) - K_{G_2}, M_{G_2}) \tag{14}$$

where K_{G_2} is the constant to prevent electricity from flowing backward, M_{G_2} is the power generation ratings capacity of the cogeneration system G_2. And the amount of the generation steam $S_{G_2}(t)$ of the cogeneration system G_2 is shown as follows.

$$S_{G_2}(t) = hpF_{G_2}(E_{G_2}(t)) \tag{15}$$

where F_{G_2} is a function of the amount of power generation of the cogeneration system G_2, and F_{G_2} is identified from results. When $\delta b_i(t)$ and $\delta_{G_2}(t)$ are decided, $R_b(t)$, $E(t)$, and

$E_{G_2}(t)$ are obtained from expression (10)-(15), Amount $G(t)$ of entire plant of consumption gas is shown as follows.

$$G(t) = \delta_{b_i}(t)H_{b_i}R_b(t) + \delta_{G_1}(t)H_{G_1}R_{G_1}(t) + \delta_{G_2}(t)H_{G_2}R_{G_2}(t) \tag{16}$$

where H_{b_i}, H_{G_1}, and H_{G_2} are constants that identified from results. Therefore, amount $E(t)$ of power consumption and amount $G(t)$ of the gas are decided, and total cost $C_0(t)$ for running the plant is shown as follows.

$$C_0(t) = E(t)C_E + G(t)C_G \tag{17}$$

where C_E and C_G are following amount charge of electric power and gas respectively.

6 Considering the factor of equipment switching The cost obtained by the expression in the preceding chapter is the cost of steady operation. There is a difference twice or more in the heat-load at daytime and night. It is necessary to switch the running equipment corresponding to the heat-load. So, it is necessary to optimize the operation plan including the switching cost. In general, the switching cost is treated as a problem each every day, and considered by adding the switching cost to the regular running cost during a day. But if the switching cost treats as a problem each every day, the number of situations of the plan increases by subdividing the unit time of the plan. Because the processing time is proportional to the number of situations of the plan, to have to obtain the plan In realistic time, there is the limit of number of subdividing the unit time of the plan. Thus it shows some methods that the switching cost is treated as the problem every unit time or the optimization problem equal with it. And those methods were applied to the data of the actual factory, and those application results were compared.

6.1 Modeling the cost of equipment switching Switch cost C_M is modeled by the following expressions.

$$C_M = C_0'(t)dt + \sum_{j=1}^{10+4+2} \delta_j(t)(1 - \delta_j(t-1))E_{0_j}T_{0_j} \tag{18}$$

where the first element is cost needed during transition in which the running equipment is switched. Because it is difficult to switch the equipments at the same time, there is a situation that both the stopping equipment and the starting equipment are running. $C_0'(t)$ is the cost needed in such situation, and dt is continuance time in the the situation.The second elements is a cost that needed in equipment startup process. E_{0_j} is the power consumption of the startup process of the equipment j, and T_{0_j} is the startup time of the equipment. Because duration of startup of the equipment changes depending on the stand-by state, T_{0_j} is a function of the stand-by state at the time of startup.

6.2 Operation of object of comparison (real plant) Next, an actual heat-load and the operation pattern of the real plant, used in comparative study here, are shown in Fig.6, 7. To exclude the factor of the prediction accuracy on the day for comparative study, the day when the thermal loading (predictive value) and results were almost equal was selected as a day for comparative study. Fig. 7 is a Gantt chart that shows the presence of running the heat source equipment (R_1-R_{10}: freezers, B_1-B_4: boilers, G_1, G_2: cogeneratioon systems) during a day, and the vertical direction is time. It is understood that the real plant corresponds to the load change in the morning and evening by switching the equipments in comparatively little frequency.

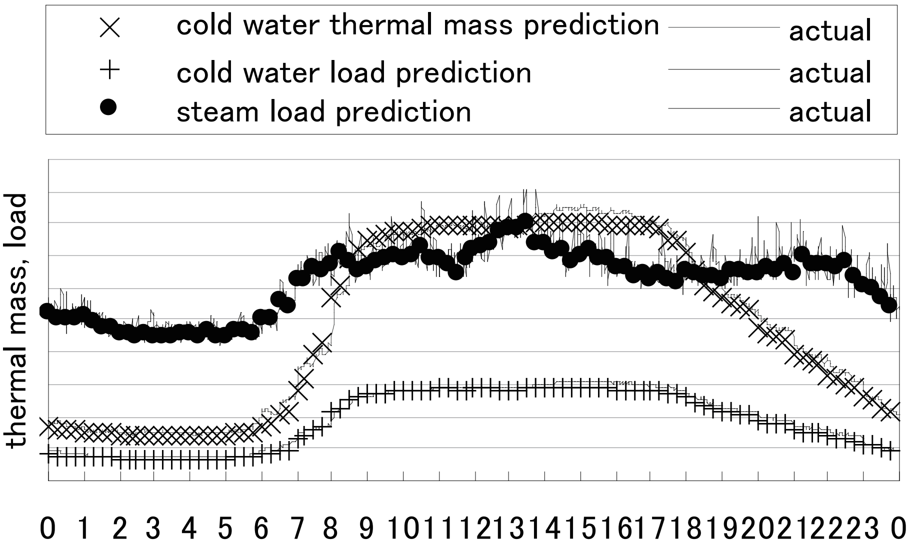

Figure 6: The heat-load on day for plan

6.3 Optimization result only considering the regular running cost The result of calculating the best cost running pattern of the equipments against the load of each unit interval, without especially limiting the switching of the equipments, is shown in Fig. 8. Though costs is small more than results, there are cases of repeating the startup and stop of the equipment at short time at about 7 AM and 18 AM, Because Startup time of the equipment cannot be secured in such cases, this plan is not executable.

6.4 The results considering the Startup time of each equipment The result of optimization of operation plan, introducing following limitation of switching the equipments to avoid the case of repeating the startup and stop of the equipment, is shown in Fig. 9.

1) Prohibition of restart after equipment stops by Startup time or less.

2) Prohibition of stop after equipment starts by Startup time or less.

Because actual equipment needs time to startup and to stop the limitation 1) and 2) is an appropriate limitation. Consequently, though the switching of the freezer was controlled to some degree, The switching of the boiler was not controlled. It is for the Startup time of the boiler is relatively short.. (B1 at 20 P.M, B3 at 18 P.M, etc.)

6.5 Switch cost consideration idea I The idea is the way to minimize cost of each unit time that is a sum of the cost of switching planned before the unit time and of the cost of regular running. The result of this idea is shown as Fig. 10. For the switching of equipments was controlled too much, the cost of this plan is almost equal to the cost of real operating plan. It is thought that this is because the switching of the equipments did not have planned by according to the load change because the switching cost is larger than the regular running costs of unit time.

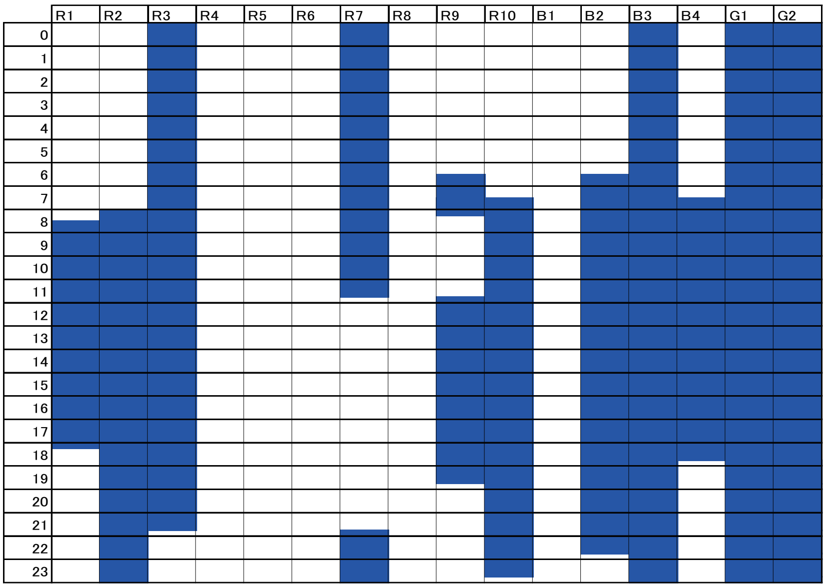

Figure 7: The actual operation pattern

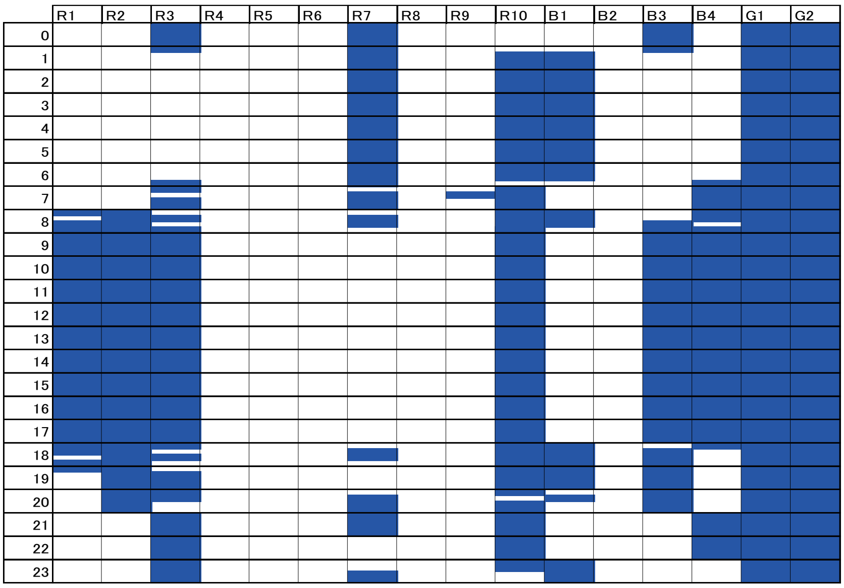

Figure 8: Optimization result in unlimited switching (Cost ratio to results: 88.85%)

6.6 Switch cost consideration idea II If the plant can run more low-cost by the switching of some equipments, the effect of the switching is effective until the state will change. The idea is a way to consider the cost of switching of the equipments as the cost of the period when the same equipments are running. However, when the switching of some equipments will be planned, the time of the next switching is not be planned yet. So the way

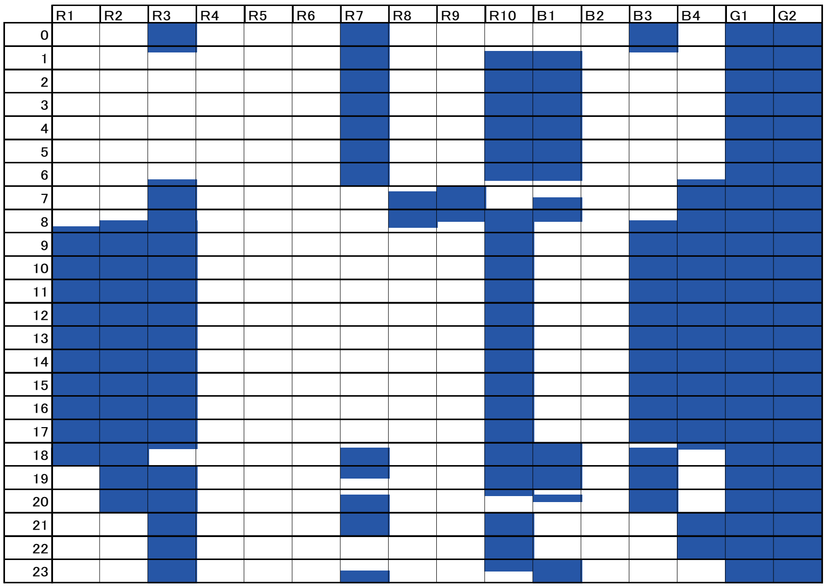

Figure 9: The result of limiting time until the next switching (Cost ratio to results: 88.78%)

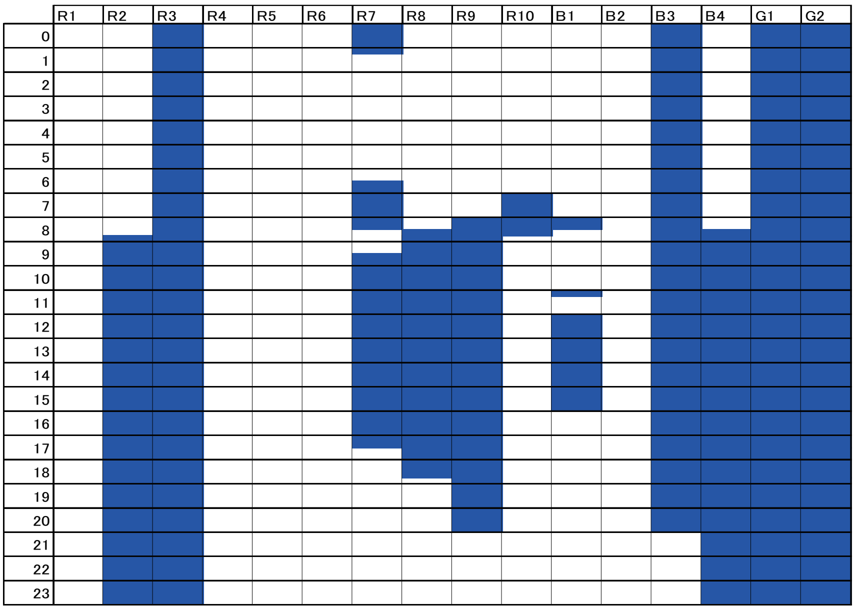

Figure 10: The result of considering the switching cost as the cost of unit-time after the switching (Cost ratio to results: 98.92%)

things are going, the optimization on unit time is impossible. So, a following assumption is introduced. • The best combination of running equipments don't change while almost the same load (that means the ratio of load against the beginning of the state is in a constant range) is continuing. By the assumption, this idea becomes the way to minimize cost of each unit time the cost is a sum of the cost of regular running and of the switching cost dividing by length of the period (in which almost the same load is continuing). The result of this idea is shown as Fig. 11. The constant range (that used as criteria for whether the load of next unit time is almost same to the load of previous unit time) was put with ± 5%.

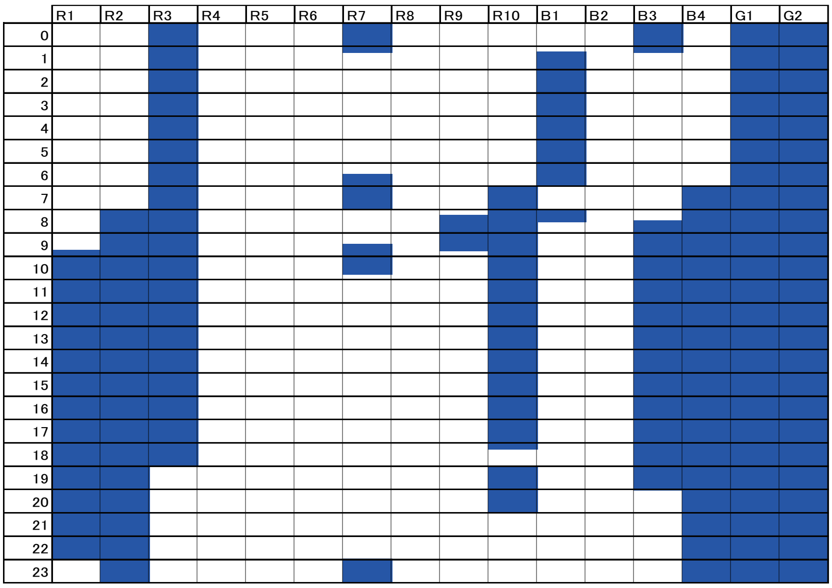

Figure 11: The result of considering switching cost as the cost of the period between the switching and the next switching (Cost ratio to results: 90.79%)

In this result, the switching of equipments was not controlled too much. But there is a useless switching in the time of morning when the load will increase rapidly. It is thought that this is because next switching had been planned at intervals that are shorter than assumption because to make a plan of next switching under the period in which the divided previous switching cost is considered was not prohibited.

6.7 Switch cost consideration idea III This idea is an improved idea of the previous one and is the way to divide day into periods when the load is almost the same and to optimize the plan of each division period. The result of this idea is shown as Fig. 12. The frequency of switching of the equipments of the result plan was almost as same as that of the real operation, and the cost of this plan is less than the cost of the real operation.

6.8 Switch cost consideration idea IV The horizontal line of Fig. 12 shows the delimitation of the divided period. Among those, red line indicates there was no switching of the equipments, and indicates same operation pattern of the equipments was continued exceeding previous period. Because the switching cost becomes relatively small against the regular running cost, there might exist more costless operation pattern for the consecutive periods in which the same operation pattern were planned. So, this idea is to optimize the operation pattern under such consecutive periods again when such consecutive periods

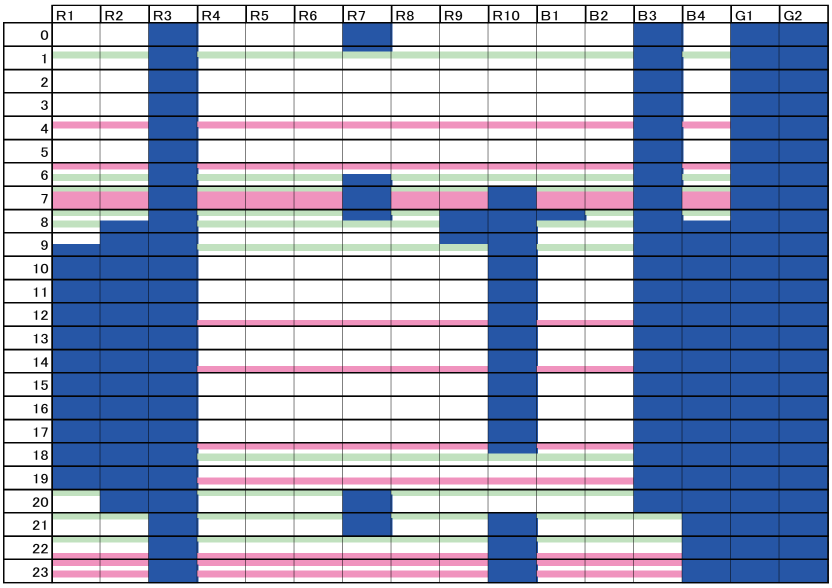

Figure 12: The result of making switching period fixed (Cost ratio to results: 90.09%)

exist. The result of this idea is shown as Fig. 13. The result plan was almost same as that of previous idea, and cost of the plan was not improved from that of previous idea.

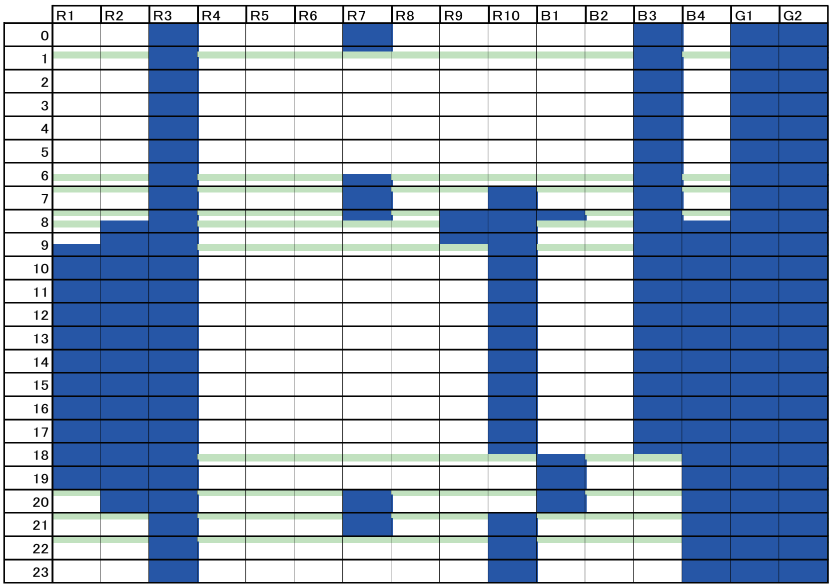

Figure 13: Result of uniting the no switching periods (Cost ratio to results: 90.09%)

6.9 Switch cost consideration idea V When switching of equipment is not necessary at the end of the period, this idea is the way to optimize the period of operating pattern optimization by extending it during the unit time. In addition, this idea is the way to optimize the period dividing condition by changing the dividing condition gradually. The result of this idea is shown as Fig. 14. Though two kinds of optimizations were done the result plan was almost same as that of previous idea, and cost of the plan was not improved from that of previous idea. According to these comparative studies, the plan that cost is almost equal to cost of more complex optimization can be obtained by using the third idea.

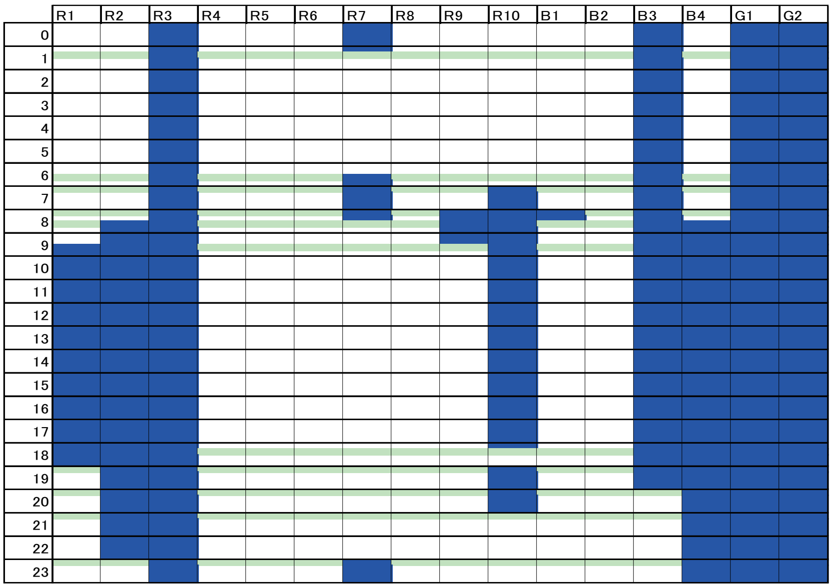

Figure 14: Result of optimizing switching period (Cost ratio to results: 90.09%)

7 Control of startup stop in a short term of a equipment In the real operation, from sides of the longevity extending the life of equipment and the preventions of the operational error, for the same equipment, operation that repeats the startup stop in a short term is not done. Even in the morning and evening when the load changes rapidly, there is only a case that some equipment was temporarily used. This factor is necessary to make a plan suitable to the real operation. So, to consider this factor, the following limitations are introduced.

1) For the period from the beginning of the day until the heat-load becomes a peak, the frequency of switching of the running equipment at the beginning of the day is limited to one times or less.

2) For the period from the beginning of the day until the heat-load becomes a peak, the frequency of switching of the stopped equipment at the beginning of the day is limited to two times or less.

3) For the period from time that the heat-load is a peak to the end of the day, the frequency of switching of the running equipment at the beginning of the period is limited to one times or less.

4) For the period from time that the heat-load is a peak to the end of the day, the frequency of switching of the stopped equipment at the beginning of the period is limited to two times or less.

Fig. 15 shows the optimization result that is optimized under this limitation by using the method that explained in the previous chapter.

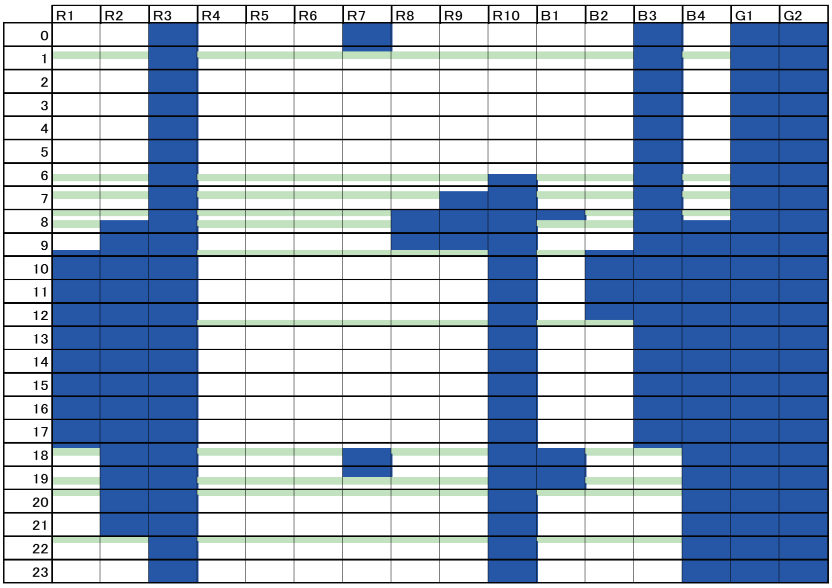

Figure 15: The result of the morning and evening's controlling start times of two or more one equipment (Cost ratio to results: 91.25%)

Compared with the result of Fig. 14, Though the cost of the result is increased for these limitations, the increment of cost was small.

8 Verification The result of optimizing the operation plan from January to July, 2009, by using the obtaining method, is shown in Table 3. However, to exclude a factor outside consideration this time, the value of results column in the table is not an actual value but a value calculated by same way used in optimization. As a result, it was confirmed that the cost of the operation plan optimized by this method is less than cost of the the real operation.

Table 3: The results of operation planning in the month

Cost of the month		Improvement rate(%)		
Optimization	Real value	Maximum	Minimum	Average
282.80	318.88	23.32	0.86	10.91

9 Conclusion To the operation planning problem of the urban district heating and cooling system, as an achievement method that the processing time don't increase unrealistically by subdividing the unit time of the plan, we proposed the method of the regional heat-load prediction, that results are used in the operation planning. In the method, the day's heat-load is predicted by the multiple regression analysis of which the explanatory variable are weather information and recent results, and then the day's heat-load is divided in proportion in the recent pattern of the heat-load. And we adopted the method to the real plant data, by considering the characteristic of weather forecasting value, we showed that the proposed method can predict the heat-load values almost near the real values. Next, we proposed some methods of operation planning of the urban district heating and cooling system, applied to the data of the real plant, and compared the application results. And we showed that the operating cost including the switching cost was optimized by method, the way to divide day into periods when the load is almost the same and to optimize the plan of each division period. In addition, by introducing limitations, we prevented the operation (startup stop in a short term of a equipment) that it is not done in real system from sides of extending the life of equipments and prevention of accidents, and we confirmed the effect. Finally, we adapted this method to one month real data and showed that the cost of the operation plan optimized by this method is less than cost of the the real operation.

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