DEVELOPMENT OF AN OPTIML OPERATIONAL PLANNING SYSTEM USING AN OBJECT-ORIENTED FRAMEWORK FOR ENERGY SUPPLY PLANTS

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ABSTRACT

An optimal operational planning system with a user-friendly interface using an object-oriented framework is developed for the purpose of determining operational strategies of energy supply plants in a simple and rational manner on personal computers. The system has the following main functions: (a) data registration, (b) plant model graphical editing, (c) automatic programming and optimization calculation, and (d) graphical representation of results.

A plant model graphical editor enables an easy and flexible composition or change of plant configurations and their relevant data by using fundamental data registered in a database. Plant data composed by the editor are arranged automatically to carry out an optimization calculation, in which the operational strategy is determined so as to minimize an objective function, such as operational cost subject to energy demand requirements and other operational restraints.

INTRODUCTION

In correspondence to the growing concern towards environmental problems, energy supply plants such as district heating and cooling systems or buildings have started introducing cogeneration, river water-utilizing heat pump, or heat storage plants, composed of various types of equipment. Since there are many alternatives for operational strategies of such energy supply plants, the planning of plant operation and evaluation of performance have become difficult. To solve this problem, we developed a software tool on workstations[1)] that assists operational planning and evaluation of energy supply plants, using optimization method based on mathematical programming approaches a few years ago. But there were a lot of requirements to use it on personal computers.

By using an object-oriented framework for CASE tool[2)], we could develop an operational planning system on personal computers in a short period and easily. In this paper, the operational planning method based on an optimization technique is first described. Second, the optimal operational planning system development using an object-oriented framework are explained. Third, several main functions of the system are explained. Finally, an application example is illustrated to ascertain the effectiveness of the proposed system.

OPTIMIZATION APPROACH TO OPERATIONAL PLANNING

Many alternatives exist concerning operational strategies. We adopt an optimal planning method using a mathematical programming approach[3)] for the optimal operational planning system. Concrete procedures of the optimal operational planning are shown in Fig.1.

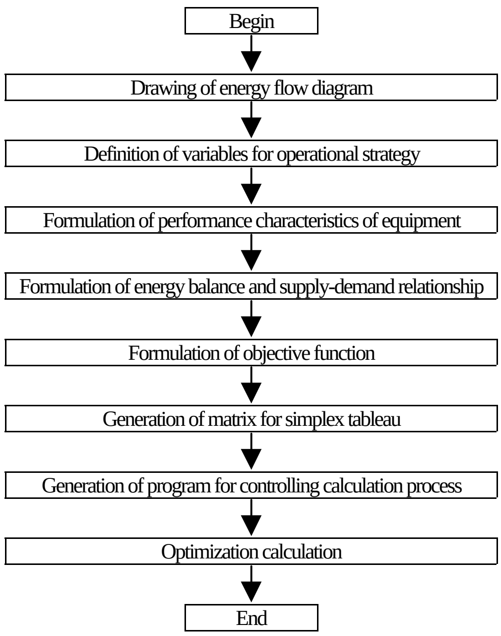

Fig. 1 Procedures of optimal operational planning of energy supply plants

A summary of each procedure is described in the following. First, an energy flow diagram is drawn which illustrates the energy conversion process from supplies to demands via equipment, and following this, the variables expressing the operational strategy are defined. They are composed of continuous and binary variables, $\boldsymbol{x}=(x_1, x_2, \ldots x_{n1})$ and $\boldsymbol{y}=(y_1, y_2, \ldots y_{n2})$, which correspond to the energy flows rates and the on/off status of operation, respectively.

Second, as performance characteristics of equipment, the relationships between flow rates of input and output energy are formulated by using the variables defined in the foregoing. These relationships are expressed fundamentally as linear ones among the variables. Here, since binary variables are employed to consider the discontinuity of performance characteristics due to on/off status, even the linear equations can express a change of efficiency due to rated/part load status. Energy balance and supply-demand relationships are also formulated for each energy flow. These are based on the first law of thermodynamics and expressed as linear equations of energy flow rates related with branching points in the energy flow diagram. All these equations are considered as constraints of the optimization problem. Furthermore, the objective function of the optimization problem is formulated by using both binary and continuous variables.

For example, the hourly operational cost could be adopted as the objective function. This optimization problem results in a mixed-integer linear programming problem, and it can be solve by using the branch and bound method along with the dual simplex method. The problem can be expressed mathematically as

$$\text{minimize} \quad \boldsymbol{f}(\boldsymbol{x}, \boldsymbol{y}; \boldsymbol{d}, \boldsymbol{c}, \boldsymbol{p}(\boldsymbol{a})) \qquad (1)$$

$$\text{subject to} \quad \boldsymbol{g}(\boldsymbol{x}, \boldsymbol{y}; \boldsymbol{d}, \boldsymbol{c}, \boldsymbol{p}(\boldsymbol{a})) = 0 \qquad (2)$$

$$x_i \geq 0, i = 1,2,...., n_1 \qquad (3)$$

$$y_i \in \{0,1\}, j = 1,2,..., n_2 \qquad (4)$$

Where *d*, *c*, *p*, and *a* are the vectors for energy demands, energy costs, performance characteristic values of equipment, and ambient conditions, respectively, and these are treated as parameters whose values are given as input data. The performance characteristic values *p* may be functions of ambient conditions *a*. This problem is defined for each representative day and each sampling time interval.

Finally, according to the foregoing formulation, the matrix for simplex tableau is generated as input data for solving the mixed-integer linear programming problem. The program for controlling the whole calculation process – data input, optimization calculation, and data output – is also generated. The optimization calculation is carried out to find the optimal values of variables expressing operational strategy.

SYSTEM DEVELOPMENT USING FRAMEWORK

Framework for CASE tool

The framework for control monitoring system designing support CASE(Computer Aided System Engineering) tool development which we used for developing the optimal operational planning system, provides object class groups for expressing and editing design information, that would assist the designing of control monitoring systems, particularly modeling and simulation. It is unique in that it not only provides graphical user interface functions, but also domain model object class groups for expressing system design information and application model object class groups for editing them visually on the computer windows.

This framework would ease the task of developing a CASE tool having functions of defining objects that constitute a system (object modeler), and building up the system by combining and connecting the defined objects (system modeler) (Fig. 2).

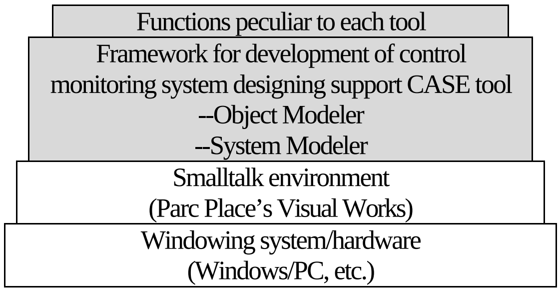

Fig. 2 Framework environment

System development procedure

In the case of the optimal operational planning system, two groups of components make up the energy plant, the equipment parts group and the energy terminal parts group. When composing an energy plant, you draw the necessary parts and connect them to express the energy flow. Figure 3 shows the results of analyzing the design information of an energy plant system by the object-oriented method and describing them by the OMT(Objected Modeling Technique) method.

We studied the results to verify that the design information to be processed by the tool could be expressed by the domain model object group provided by the framework. Then, with the help of tool users and specialists, or supervisors, we defined the actual equipment parts and energy terminal parts, and decided on the specifications after studying which functions are necessary for the actual tool, and also the operability, thus completing the development.

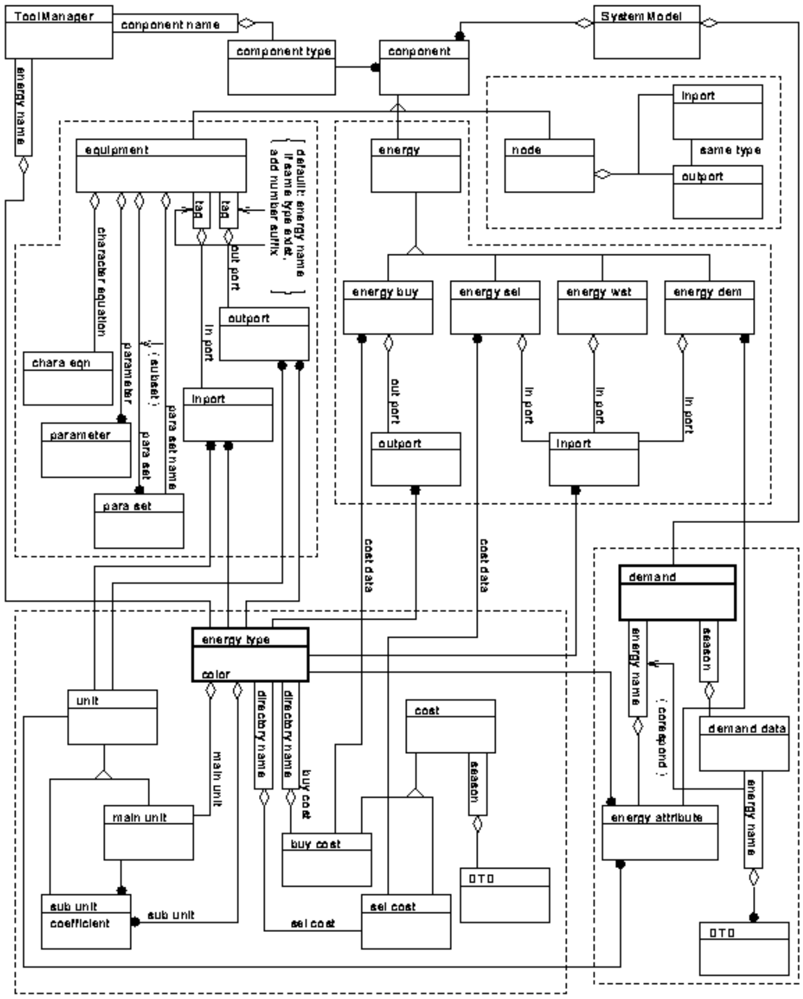

Fig. 3 Results of object-oriented analysis of system design information

Benefits of development using framework

Through the process of developing this tool, we were able of ascertain the following benefits regarding the use of framework.

1 Ease of analyzing and designing: Regarding the design information processed by the tool, we only need to select or allocate objects to match the domain model object structure provided by the framework. If we know that the results of analysis can be expressed by the framework objects, there would be no turn-back from object designing and actual installation afterwards. This is one of the benefits of object class groups being provided to the framework for expressing information unique to a particular problem field.

2 Participation of specialists of particular problem fields to tool development: As a general-purpose object definition editor and a general-purpose system designing editor are provided by the framework, specialists of particular problem fields---those who are not familiar with object-oriented languages such as Smalltalk or C++---can also define object groups constituting the system, or prototype system models using them. As a result, we were able to acquire primarily demanded functions from users' viewpoint at an early stage, and to check closely, matters such as selection of necessary editors and how user-operability ought to be.

OPTIMAL OPERATIONAL PLANNING SYSTEM

The fundamental structure of the optimal operational planning system developed here is shown in Fig. 4. The system has the following main functions:

(a) energy type registration,
(b) equipment type registration,
(c) demand data registration,
(d) plant model graphical editing,
(e) operational restraints setting,
(f) optimization calculation,
(g)graphical representation of results.

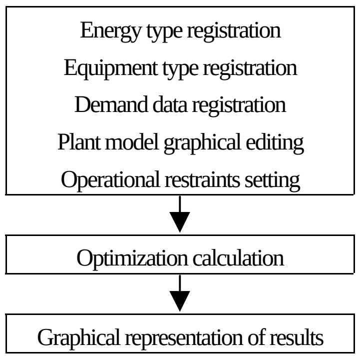

Fig. 4 Fundamental structure of the optimal operational planning system

Energy type registration function

A function to define the energies consumed by the energy supply plant to be evaluated. Planners define which color, line type, or line width to use to indicate specific energy when drawing a plant model on the Energy Type Definition windows, as well as its engineering unit, purchasing cost, and selling cost (in case of selling power when there is surplus). All energies related to the plant, such as energies purchased by the plant, energies supplied to the demands, and input/output energies of heat source equipment, must be defined. The whole energy data is defined by this window.

Equipment type registration function

A function to define the heat source equipment composing the plant. Three items ---input/output energies of equipment (which must be one of the energies defined on the Energy Type Definition windows), icon (icon used when drawing a plant model), and performance characteristics (primary approximate equation and its coefficient)---must be defined on the windows shown in Fig. 5.

Any equipment can be defined, as long as the input and output energies and the relationship between them are identified. When there are more than two equipment of the same kind but with different capacities, planners only have to define the performance characteristic coefficients that differ, instead of defining the whole equipment repeatedly. The performance characteristics of equipment are defined by this window.

Demand data registration function

A function to register the demand data of the energy supply plant to be simulated, according to energy type and time zone. Demand data is registered by this window.

Fig.5 Equipment Type Definition window

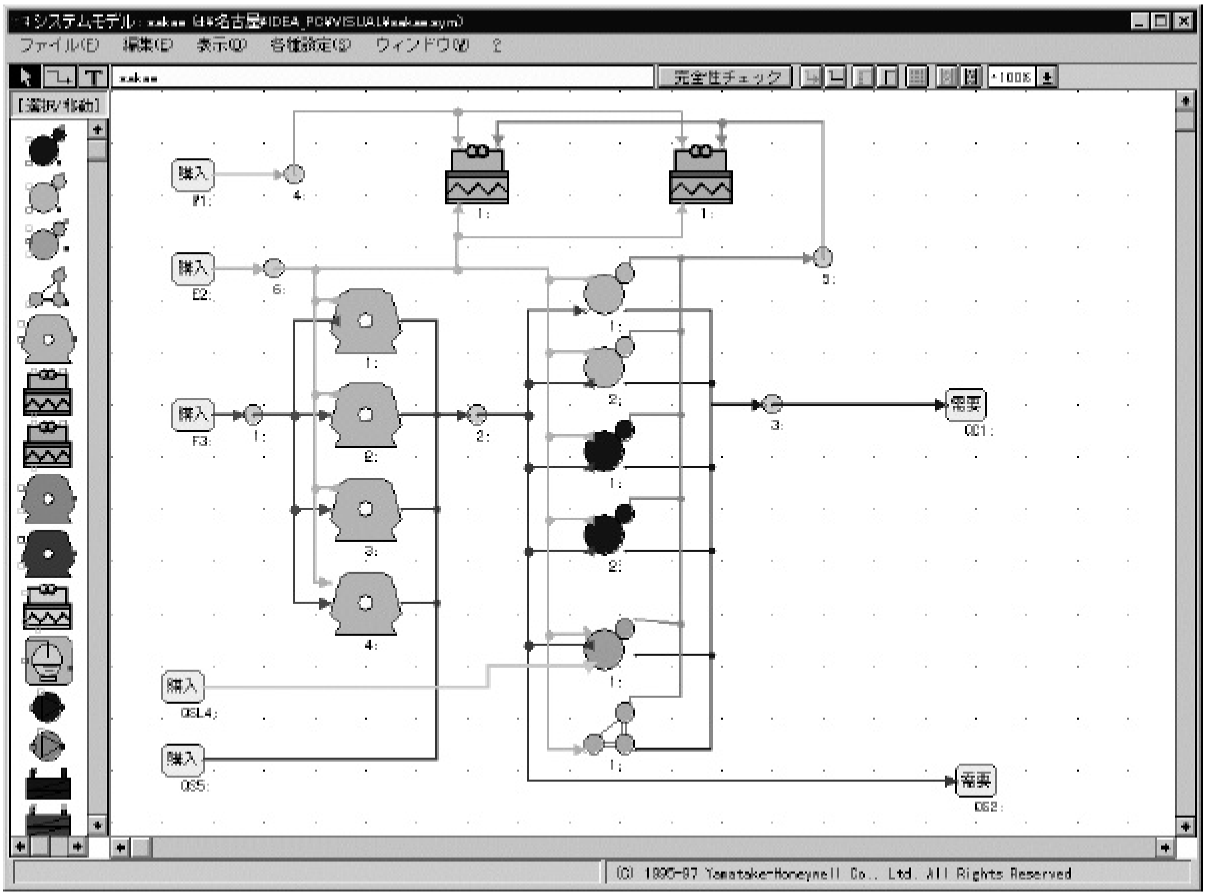

Fig. 6　Example of a plant energy flow diagram drawn by graphical editor

Plant model graphical editing function

Functions to edit the energy flow diagram of the energy supply plant by using GUI. The energy supply plant optimal operational planning system automatically completes the formulation task from the energy flow diagram, and generates a plant model. Fig. 6 shows an energy flow diagram of an energy supply plant.

The process of editing a plant model is as follows.

1 From the palette displayed on the left side of the window, where equipment defined on the Equipment Type Definition windows are shown, select the desired equipment and arrange their icon on the System Model window.

2 Connect each equipment with lines (energy).

3 Click the right button of the mouse with the pointer on the icon, and set the information necessary for each equipment, demand, and purchase icon. (Which performance characteristic coefficient to use for an equipment icon, type of energy for a demand icon, and which purchasing cost to use for a purchase icon.)

When all above tasks have been completed, planners can check whether the model is ready for calculation. Select the “Completion Check” button found on the upper middle of the window, and it will tell planners if optimization calculation formulation can be performed. If “Completion Confirmed” is outputted, it is ready for calculation. If not, it will tell planners which parameter has to be set, or which lines have to be connected.

Operational restraints setting function

Optimization calculation can be performed above mentioned tasks have been completed. However, if there are any condition planners wish to add, like changing the objective function or stopping certain equipment during specific time zone, planners need to set them on the Operational Restraints Setting windows.

Operational restraints planners can set are four items. These are objective functions (default value is operational cost), evaluation items (items not represented in the system model; for example, if planners wish to know the CO_2 emission from power generated by cogeneration, which is an item not defined as part of the equipment’s performance characteristics, planners may set it here), operational constraints (forced on/off of equipment, fixed part load rate of running equipment, etc.), and parameters which provide necessary parameter values to these items.

Optimization calculation

The operational planning can be carried out automatically for energy supply plants defined by the graphical editor. That is, all the procedures needed for the operational planning described in the foregoing – formulation of the optimal operational planning problem, generation of the matrix for simplex tableau and the program for controlling whole calculation process, and execution of optimization calculation – can be performed automatically by analyzing energy flow diagrams and converting them into numerical and character data. This function enables planners to conduct the operational planning easily and efficiently without doing so manually.

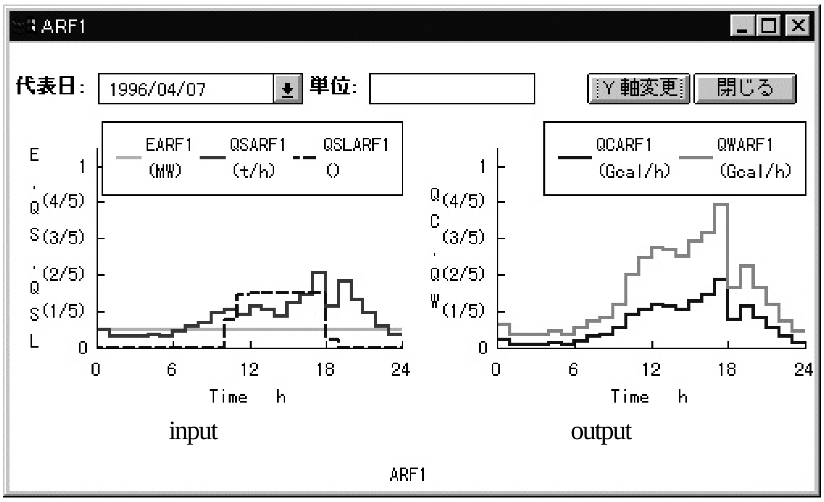

Fig. 7 Example of a calculation result

Graphical representation of results

After optimization calculation, planners can check the results immediately on the windows, and by clicking the part planners wish to see on the energy flow diagram. Fig. 7 shows a graphical representation of the optimal operational strategy. These windows can not display the results in detail. If planners wish to evaluate the results thoroughly, planners can use the calculation result file stored as a CSV file and analyze the data using spread sheets, etc.

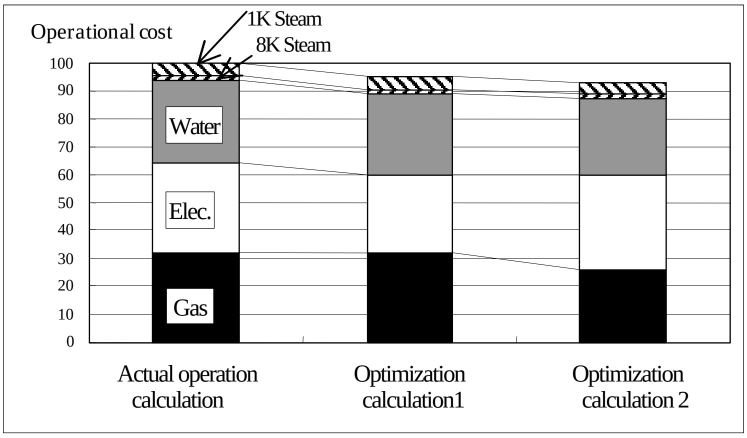

Fig. 8 Performance evaluation results

APPLICATION EXAMPLE

The system has been applied to the optimal operational planning of a district heating and cooling plant. Fig. 6 shows the configuration of this plant. The plant is equipped with four double effect steam absorption chillers (R-1,R-2,R-3,R-4), one single effect steam absorption chiller(R-6), one electric centrifugal chiller (R-7), six cooling towers, and four gas-fired steam boilers. Purchased energies are electricity, natural gas, city water, and the 8k and 1K exhaust heat steam from the gas engine generator owned by the building where the plant is located. The energies supplied to the demands are chilled water and steam.

At this plant, three types of operational planning were performed with the operational cost as the objective function.

1 Actual operation calculation

Planning performed with operator's on/off schedule for heat source equipment set as the operational restraint. This calculation aims to eliminate the optimization calculation model error from the difference between optimization calculation results.

2 Optimization calculation 1

Planning performed with the operational restraint assigning a electric centrifugal chiller for backup. This is how the plant is operated at present.

3 Optimization calculation 2

Planning performed without any operational restraints..

The results of the planning are shown in Fig. 8. It tells us that another 5% operational cost reduction is possible in optimization calculation 1, and 7% in 2.

The difference between the operational costs of actual operation calculation and optimization calculation is rather unclear from this figure , so we have charted the operation of heat source equipment of a representative day from the planning result data (Fig. 9).

R-1 and 2 each has two chilled water/cooling water pumps of the same capacity, and becomes a 500RT absorption chiller when a single pump is running. Actual operation calculation and optimization calculation 1 may seem the same at first glance, but actual operation runs two R-1 pumps (1000RT) while optimization calculation 1 runs only one, which accounts for the difference in the electricity charges shown in Fig. 8 (gas and water charges are almost the same).

The reason for the operator's judgment to run two pumps instead of one, is to allow for some spare in the flow on the heat source side against demand for chilled water (Fig. 10). However, if it is operated to barely manage the demand, as in optimization calculation 1, the operational cost can be reduced by approximately 5% from the current operation. The optimization calculation 2 tells us that if R-1 of optimization calculation 1 is changed to R-7 centrifugal chiller, electricity charges rise but gas and water charges go down, which makes another 2% reduction of cost from optimization calculation 1 possible.

From these results, we understand that the operator operates the plant in its optimal condition, considering the risk against demand for chilled water from the demand side. However, if it is operated to barely manage the demand, the operational cost can be reduced by about 5%, and when a electric centrifugal chiller is used for normal operation instead of for backup, 7% reduction is possible.

By using this system, we can evaluate the performance of the current energy supply plant easily and thoroughly.

CONCLUSIONS

A optimal operational planning system on personal computers has been developed to assist planners in determining operational strategies for various types of energy supply plants. This system not only has a rational basis on an optimization technique, but also incorporates a user-friendly interface to reduce planning task and time.

The main features of the system are summarized as follows.

1 The system can be used on personal computers.

2 The operational strategy can be determined

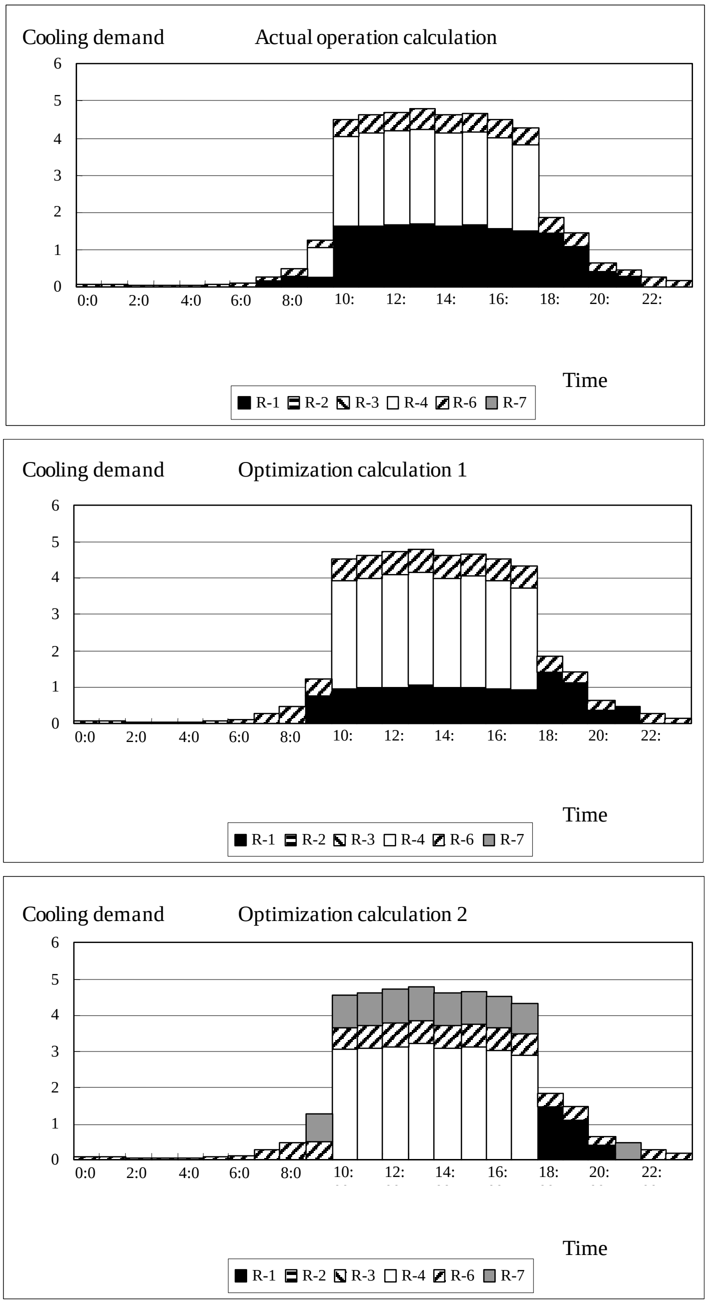

Fig. 9 Heat source operational planning

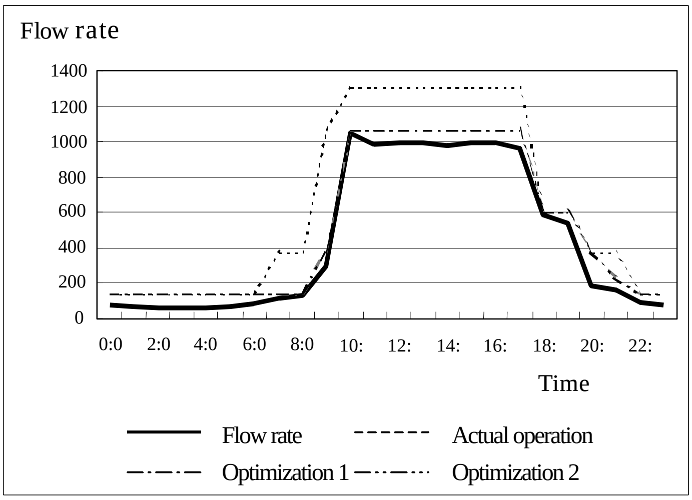

Fig. 10 Chilled water flow rate

rationally and systematically by the optimization approach, because this approach does not need to assume any operational rules by trial and error.

3 The function of graphical editing enables an easy and flexible composition or change in plant configurations and their relevant data.

4 The function of automatic programming and optimization calculation enables an easy and efficient determination of operational strategies.

5 The function of graphical representation of results enables an easy and flexible evaluation of energy supply plants corresponding to planners needs.

Because of these features, the system developed here will be a useful tool for the operational planning of energy supply plants from the viewpoints not only of rationality, but also of task and time reduction.

REFERENCES

1)Yokoyama, R., K.Ito, F. Miyasaka and K. Kamimura, “Development of a General-Purpose Optimal Operational Planning System for Energy Supply Plants”, Transaction of the ASME pp. 290-296 / Vol. 116, Dec. 1994

2)Nishi, Y., T. Mishima, N. Shibata and K. Nakazawa, “Object-Oriented Framework Based Development of Optimal Energy Supply Planning System”, Annual meeting paper s of IPSJ pp.109-110 , 1996

3)Horii, S., K. Ito, and Y. Suzuki, “A computer-Aided Planning (CAP) System for the Gas Engine Cogeneration Plant”, International Journal of Energy Research, Vol. 11, pp. 491-505