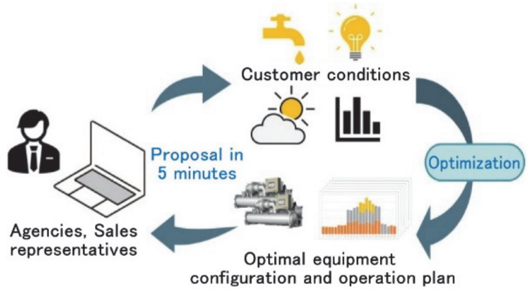
Optimization Program for Machine Combinations that Minimizes Initial Costs and Operational Costs in Heat Source Configuration



NAOKI YAMADA[*1] KOKI TATEISHI[*2]

Mitsubishi Heavy Industries, Ltd. sometimes proposes a heat source configuration that combines multiple chillers that start, stop, and partial-load operate in certain cases. In such cases, there are a large number of options to select from when considering combinations of chillers of different capacities and models, and therefore finding a combination of equipment that minimizes costs while satisfying customer requirements needs experienced designers and takes a lot of time. To solve this issue, by applying an optimization technique that combines mathematical optimization and genetic algorithm, we realized a technology that can obtain the optimum equipment combination that meets customer requirements in a short time. We summarized the developed technology in this report.

1. Introduction

Mitsubishi Heavy Industries, Ltd. (hereinafter referred to as MHI) proposes a heat source configuration that combines multiple chillers to meet the operating conditions required based on the customer's facility plan. The operating conditions include not only the application, but also the temperature in the region where the heat source equipment is installed, the load requirement, and the number of operating days. In addition, the voltage and frequency of the electric motor, the starting method, and other conditions are specified, and the models that meet the conditions are selected as candidate models. Proposals should be made by combining several of the candidate models so that the equipment configuration can be used in actual operation. An equipment configuration that can be used in actual operation means that the capacity is sufficient for the load requirement in the operating conditions and that the operation can be continued even when some of the chillers fail. Specifically, it is necessary to select an equipment configuration capable of distributing the time-varying load requirement to multiple chillers so that each chiller can partial-load operate within its operating capability range, and enable operation that satisfies the load requirement even if any one of the chillers in the equipment configuration fails or is out of service because of maintenance. While considering these necessities, the equipment configuration proposal needs to be made so that the sum of the initial costs (initial costs of the chillers to be installed) and the operational costs (annual power consumption, water charges, and maintenance costs) is minimized.

However, the number of combinations of candidate chiller models with different capacities is huge, and the selection needs to be made based on a long-term process by designers with expert knowledge, which requires time to respond to inquiries as shown in **Figure 1**. This report describes the application of optimization technology to this business issue and a case example of automatic selection realized thereby.

*1 Control Systems Research Department, Research & Innovation Center
*2 Research Manager, Control Systems Research Department, Research & Innovation Center

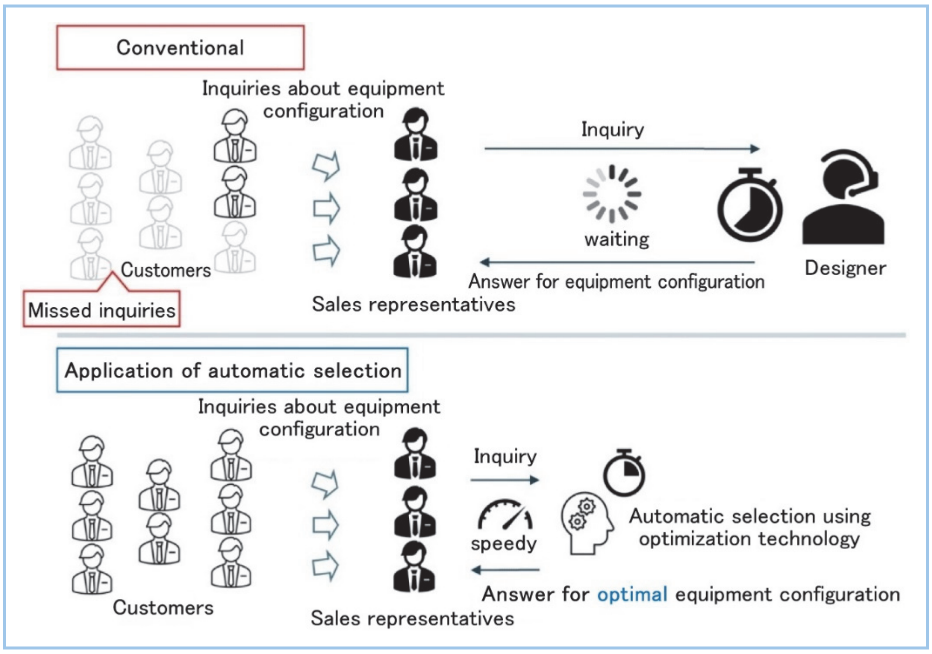


Figure 1 Automation of responding to inquiries about equipment configuration

2. Optimization technology

2.1 Hybrid optimization technology of mathematical optimization and genetic algorithm

The optimization calculation generates the equipment configuration that minimizes the sum of the initial costs and the annual operational costs. However, since the operational costs vary depending on the start/stop and load distribution of each chiller, identifying an operation plan that minimizes the operational costs is necessary. Therefore, formulation for the optimization calculation was conducted separately for (1) optimization calculation of the operation plan (operation plan problem) and (2) optimization calculation of the equipment configuration (arrangement plan problem), as shown in **Figure 2**. (1) The optimization of the operation plan was formulated as a problem of minimizing the operational costs of each chiller with start/stop and load as variables at each time. The operation plan problem is a mixed integer programming problem involving nonlinear characteristics of chillers and has a large computational scale, so the computational scale was reduced by approximating the characteristics with a combination of linear equations and fast solution finding was achieved by using mathematical optimization. (2) The optimization of the equipment configuration was formulated as a problem of minimizing the sum of the operational costs obtained in (1) and the initial costs, with the number of installed units of each model as variables. As the optimization method, a genetic algorithm was adopted that can employ nonlinear constraints such as a backup equipment constraint (i.e., the equipment configuration must be such that operation can continue even if any one of the equipment units fails) and that can handle discrete variables representing the number of installed units. Thus, with hybrid optimization technology that combines the two optimization methods, efficient solution finding against a large-scale optimization problem with nonlinear constraints was achieved.

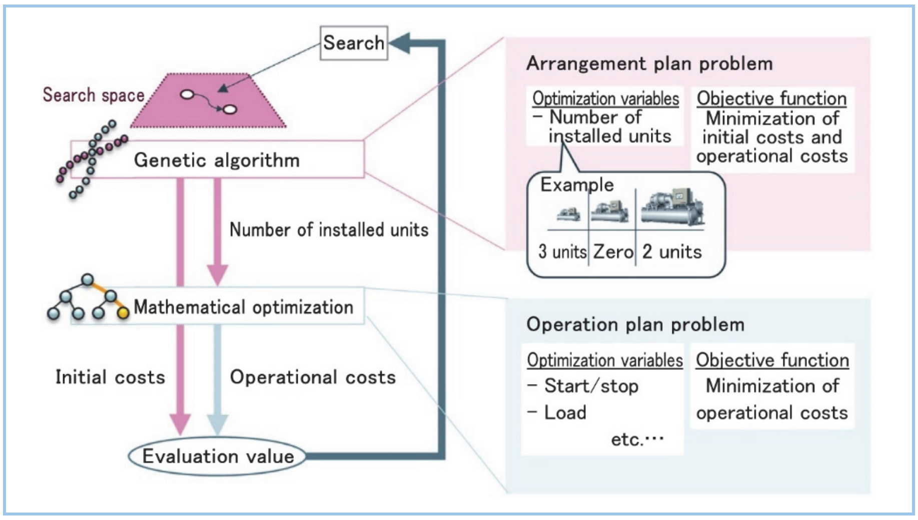


Figure 2 Hybrid optimization that combines mathematical optimization and genetic algorithm

2.2 Time series constraints in operation plan optimization

As mentioned above, operation plan optimization is an optimization issue to minimize the operational costs by using start/stop and load of chillers at each time as variables. However, since it is necessary to generate an operation plan that can be used in actual operation, it does not assume, for example, an operating situation in which the chillers are repeatedly started and stopped in a short period of time. Therefore, in this optimization, time series constraints (i.e., the minimum operating time, which is the minimum time between start and stop, and the minimum stopping time, which is the minimum time from a stop to restart) were employed. (1)

Figure 3 shows operation plan examples employing the time series constraints. It was confirmed that the chillers are not repeatedly started and stopped due to the employment of the time series constraints.

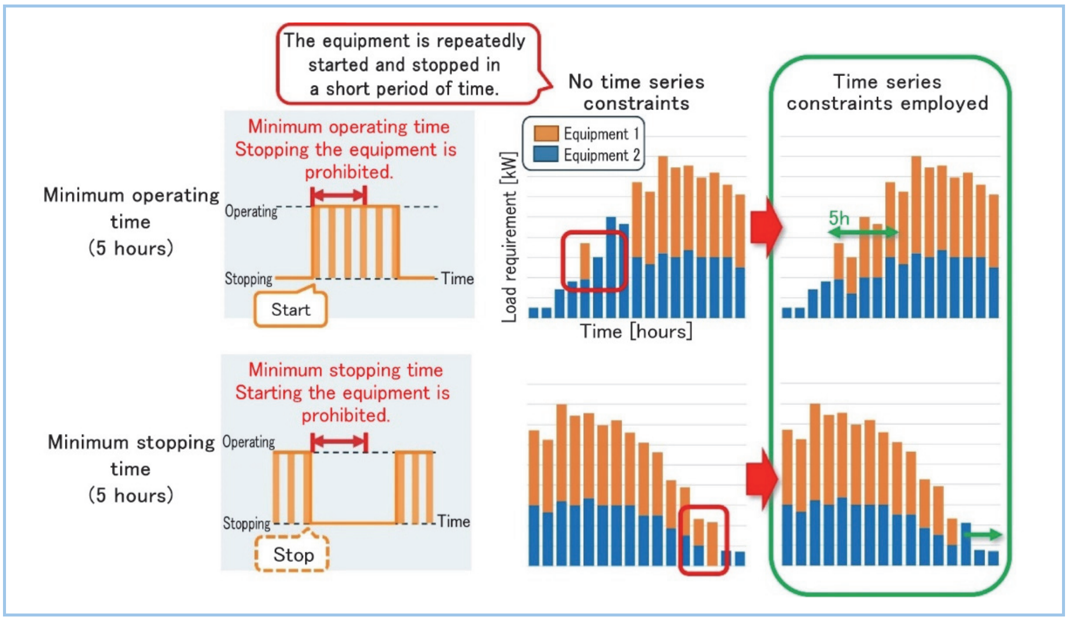


Figure 3 Results of operation plan optimization employing time series constraints

The graphs representing the results of the operation plan optimization indicate the load requirement [kW] on the vertical axis and the time on the horizontal axis. This figure shows operation plans for a configuration consisting of Equipment 1 and Equipment 2, and indicates the load [kW] of each equipment the sum of which satisfies the load requirement. In the example of the minimum operating time shown in the upper graphs, Equipment 1 is not stopped within a short time (5 hours) after being started. In the example of the minimum stopping time shown in the lower graphs, Equipment 2 is not started within a short time (5 hours) after being stopped.

2.3 Optimization of equipment configuration employing backup equipment constraint

In the optimization of the equipment configuration, the backup equipment constraint is employed. The backup equipment constraint is intended to ensure that the equipment configuration can continue the operation satisfying the load requirement even if any one of the equipment units fails. Chillers have a minimum operable load and a maximum operable load. Therefore, the backup equipment constraint cannot be satisfied simply by installing an extra chiller with the highest capacity in the equipment configuration in the case where the load requirement fluctuates greatly. In the optimization of the equipment configuration, after confirming that the obtained equipment configuration satisfies the backup equipment constraint, the sum of the operational costs and the initial costs are calculated based on the results of the optimization of the operation plan, and then the equipment configuration that minimizes the costs is calculated.

Figure 4 shows the equipment configuration and total cost with the backup equipment constraint employed. When the backup equipment constraint is not employed, a single chiller with a capacity close to the maximum load value of the load requirement is selected, whereas when the backup equipment constraint is employed, three chillers with a capacity of about 50% of the maximum load value are selected. Although the installation of the backup equipment, which generates a surplus of chillers, results in an increase in the total cost, it is confirmed that this combination allows operation to continue even if any one of the equipment units fails.

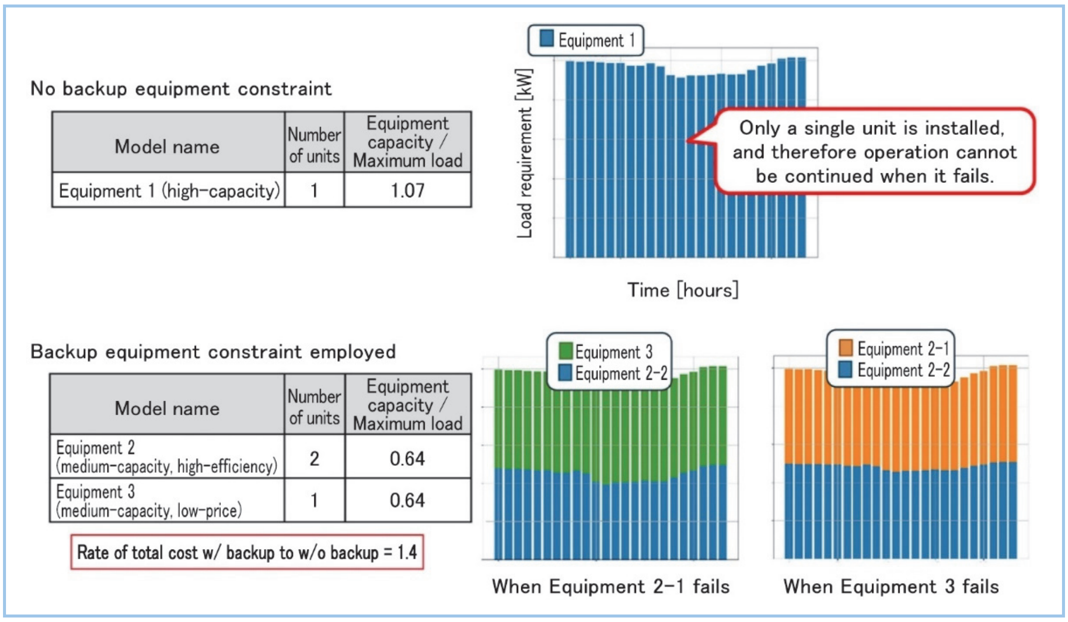
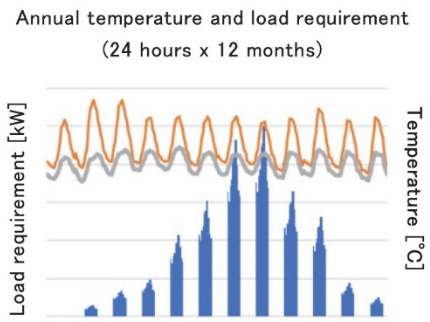


Figure 4 Results of equipment configuration optimization employing backup equipment constraint

2.4 Verification results

This section describes the results of optimization calculations of the operation plan and equipment configuration, which were performed, provided that up to eight chillers could be installed from 20 different models. It was confirmed that all calculations for 12 calculation conditions tested were completed within five minutes. It was also confirmed that the sum of the operational costs and the initial costs of the equipment configuration found as the optimal solution was the smallest among the sums calculated for all equipment combinations.

Figure 5 shows the calculation conditions (annual temperature and load) and the selection results as an example of optimization described above. In addition, as a case example of manual selection, an equipment configuration consisting of three units of the same model B was selected, and its initial costs and operational costs were calculated. In the optimization case, an equipment configuration that combines models A and B, which have different capacities, was selected, reducing costs by about 7% compared to the configuration that resulted from the manual selection.



Selection results

	Unit 1	Unit 2	Unit 3	Cost (rate to manual selection cost)
Optimization	Model A	Model B	Model B	0.93
Manual selection	Model B	Model B	Model B	1.00

Figure 5 Calculation conditions (temperature and load requirement) and optimization result of automatic equipment selection

3. Example application to sales support system

In our heat source plant business, we have been enhancing our sales support system for overseas agencies to accelerate the shortening of the lead time in responding to inquiries by automating the process of chiller configuration plan consideration at overseas agencies. The sales support system allows automatic selection and quotation of a single chiller based on the database of the core system by having overseas agencies input customer conditions into the system, thus realizing speedy responses to inquiries. However, because the system was designed only for the selection of a single chiller, equipment configurations consisting of multiple chillers needs preliminary determination and then manual selection of the combination; it takes about one month to respond to inquiries about such configurations.

To solve this issue, we applied our optimization technology to the sales support system to enable automatic selection of equipment configurations. Overseas agents can easily fill out the input items as customer conditions. For numerical data of temperature and required load, which are difficult to input, we developed a function that automatically generates data by using the database of the core system by selecting the country, use of operation facilities (factories, commercial facilities, etc.), and maximum required load prepared as options. **Figure 6** shows an overview of the input/output of the equipment configuration optimization function in the sales support system. With the introduction of this technology, it becomes possible to automatically select the equipment configuration that minimizes the cost with simple input within 5 minutes, enabling speedy proposals.

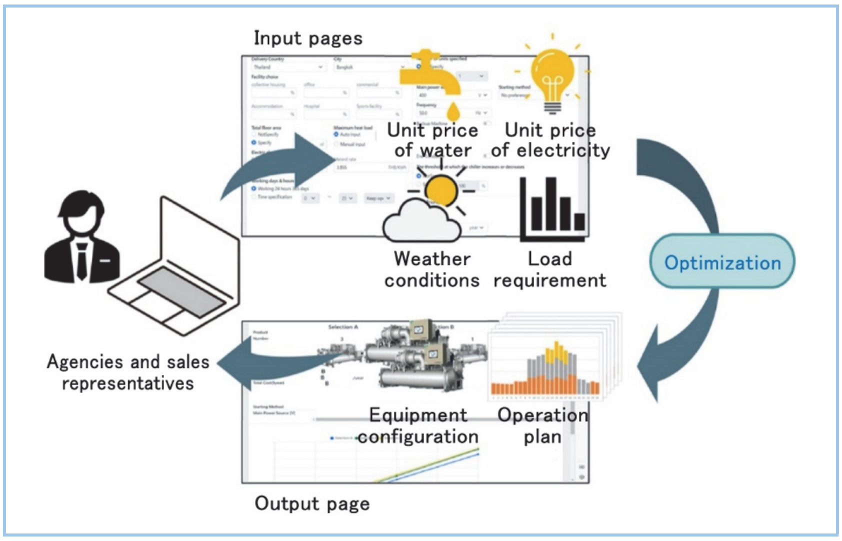


Figure 6 Overview of input/output of equipment configuration optimization function

4. Conclusion

MHI proposes heat source configurations that combine multiple chillers and minimize costs. This paper introduces the technology to solve the optimization of operation plan which minimizes operation cost and the optimization of equipment configuration which minimizes operation cost and introduction cost at high speed by using hybrid optimization which combines mathematical optimization and genetic algorithm. Furthermore, we have implemented a chiller equipment configuration optimization function using this technology in the sales support system operated in our heat source plant business, and confirmed that automatic selection of the optimum equipment configuration is enabled. As a result, we can now provide answers to composition examinations that previously took 1 month through manual selection, in just 5 minutes. We will use this function to increase the number of inquiries about equipment configurations and expand orders.

In the future, we will promote the deployment of this technology to our other products. In addition, we plan to collect feedback from users of the sales support system and continuously update the system to improve its usability as an automatic selection function.

References

(1) Bendotti, P. et al, The Min-up/Min-down Unit Commitment polytope, Optimization Online (2016)