Mathematical Application Technology for IoT Solutions

MATSUI, Tetsuro* MURAKAMI, Kenya* TANGE, Yoshio*

ABSTRACT

As the Internet of Things (IoT) becomes increasingly widespread, devices which have conventionally not been connected to a network will become connected, and likewise, data which traditionally could not be measured will be collected and analyzed. It is very important that the wide variety of collected data should be used to discover and provide value. In order to achieve this, Fuji Electric has developed a mathematical application technology for data analysis and optimization. The latest mathematical application technologies are being applied to various types of products and systems. These technologies include anomaly diagnosis technology for batch processing, anomaly symptom detection based on ensemble prediction, and a technology for visualizing potential energy savings via formula manipulation optimization.

1. Introduction

The Internet of Things (IoT) is a concept of creating new value by having a connection between things and humans via a network. In the industrial sector, especially in the manufacturing industry, networks of various devices, such as industrial networks, have long been constructed in the business sites, which allows adequate monitoring and control of large plants. As the IoT becomes increasingly widespread, devices which have conventionally not been connected to a network will become connected, and likewise, data which traditionally could not be measured will be collected and analyzed. Once a wide variety of data have been collected, the point is how the data can be used to discover value and provide it to customers.

Fuji Electric has developed the following mathematical application technologies for data analysis, optimization and other applications and utilized data through products and systems to provide value(1)(2):

(a) Proprietary neural network technology for contributing to efficient and stable operation of plants by high-accuracy prediction and anomaly diagnosis
(b) Meta-heuristic optimization technology suited for mathematical programming and nonlinear large-scale optimization problems to formulate optimum plant operation plans and minimize costs
(c) PID control technology and model predictive control technology for multi-variable systems as well as control performance monitoring technology for monitoring control performance degradation caused by characteristic change of the controlled object, all of which are used to enable stable plant control

This paper gives an overall picture of mathematical application technologies related to IoT solutions and presents the latest mathematical application technologies.

2. Overall Picture of Mathematical Application Technologies Related to IoT Solutions

Fuji Electric thinks of IoT solutions as ones that make use of data analysis and artificial intelligence technologies to deal with problems in industrial plant and social infrastructure fields for anomaly diagnosis, prediction and estimation and uses those results as the basis for optimization and creation of new value (see Fig. 1).

Anomaly diagnosis uses data analysis technology to very accurately diagnose what is occurring in a component or system and what is causing it. Up to now, for plant monitoring and control systems and various types of manufacturing equipment, the upper or lower threshold value that provides a criterion for an anomaly has been set for each measurement item to see if it is exceeded, so as to monitor plant conditions. In the future, detailed data in large volumes for the entire monitored object will become available for collection more than ever and monitoring the changes in those data on the whole is expected to be useful for prompt anomaly diagnosis.

For prediction and estimation, a model constructed by data analysis is utilized to predict the future conditions of the monitored object and estimate the values of variables not directly measured. In a large plant, for example, operating while predicting future changes allows the burden on the operators to be reduced and safer and securer operations to be realized.

For optimization and new value creation, what is

* Corporate R&D Headquarters, Fuji Electric Co., Ltd.

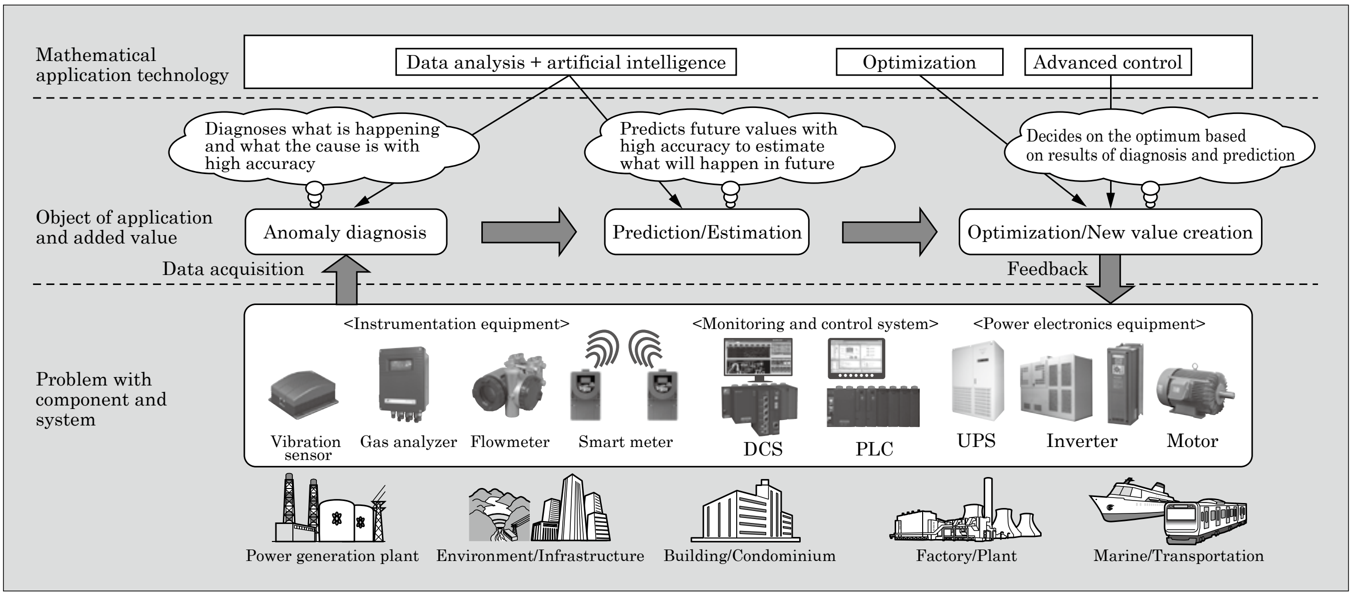

Fig.1 Overall picture of mathematical application technologies related to IoT solutions

Table 1 Representative mathematical application technologies

Classification	Technology	Outline
Data analysis technology	Anomaly diagnosis technology for continuous processing	Automatically detects abnormal states (states different from the usual) of plants by analyzing large volumes of data.
	Anomaly diagnosis technology for batch processing	Carries out anomaly diagnosis for batch processes, in which process values are not constant but the correlations between variables change in the middle.
	Quality prediction technology	Predicts quality indicators of end products based on the data measured during manufacturing and intermediate inspection results.
	Quality simulation technology	Uses trial manufacture or simulation to find the quality under the manufacturing conditions determined by design of experiments, models the manufacturing conditions and quality and searches the model to estimate the optimum manufacturing conditions.
	Soft sensing technology	Builds a mathematical model between data measurable online and data difficult to measure for estimation of data difficult to measure online.
	Event pattern extraction technology	Analyzes accumulated event log data to automatically extract patterns that appear frequently.
	Anomaly symptom detection based on ensemble prediction	Predicts learning data and input variables, which were conventionally determined by experts' close examination, by preparing multiple patterns according to simplified rules and placing emphasis on a model offering high accuracy for prediction.
	Abnormality avoidance operation presenting technology	Searches past event log data of plants to present as candidates operation procedures for abnormality avoidance carried out by operators.
	Structure health monitoring technology	Calculates the maximum acceleration and maximum story drift based on data measured by vibration sensors.
Optimization technology	Energy plant optimum operation technology	Automatically formulates the operation plans for energy supply plants that minimize the fuel costs while supplying energy to cover required demand in the proper quantity.
	Energy demand prediction technology	Predicts the maximum and minimum demand as well as demand at 24 points for every hour of the following day based on the calendar and such meteorological data as highest temperature and weather.
	Comprehensive store optimization technology for supermarkets and convenience stores	Optimizes operation (shutdown state and energy balance) of air conditioners and showcases in supermarkets and convenience stores to realize energy saving and reduction of environmental burden.
	Technology for visualizing potential energy savings via formula manipulation optimization	Applies the latest formula manipulation technology to analyze the optimization model for energy supply plants for visualizing the range of operation, thereby identify theoretical potential energy savings and limits.
	Delivery plan optimization technology	Determines the optimum route (allocation to individual vehicles and order of delivery) in delivery of packages from one delivery base to customers (destinations) by using multiple vehicles.
Advanced control technology	Control performance monitoring technology	Out of many control loops, efficiently finds those requiring improvement by using 4 indicators to quantify control performance for evaluating performance of a control system.
	Control parameter tuning technology	Identifies a plant model by using input and output data (MV and PV) of a plant to calculate PID parameters that satisfy the specification requirements (settling time, overshoot, etc.) of control.
	Model predictive control technology	Predicts future changes in a plant by using a model of the controlled objects and provide control while determining the optimum manipulated variables that keep the controlled target within the target value range.

the optimum is determined based on the results of diagnosis and prediction, which is fed back to problems in the real world. Such feedback is repeated for solving problems. Table 1 lists Fuji Electric's representative mathematical application technologies.

Of the results of the latest research and development, the following chapters present anomaly diagnosis technology for batch processing, anomaly symptom detection based on ensemble prediction and a technology for visualizing potential energy savings via formula manipulation optimization.

3. Anomaly Diagnosis Technology for Batch Processing

Recently, in the industrial and consumer fields, there are increasing demands for equipment maintenance and manufacturing quality management in the manufacturing process. A batch process, which is a type of manufacturing process, refers to one in which material feeding, processing or manufacturing, and delivery of products or partly-finished products are repeated using the same facility and equipment. In this paper, objects involving repeated similar handling by equipment and devices are generally referred to as batch processes. For example, they may indicate cooling equipment such as a refrigerated showcase to be described as an application example, in addition to a polymerization process in the chemical industry, semiconductor manufacturing process and injection molding process.

In batch processes, many sensors have come to be installed in various devices along with the progress of sensor technology to enable on-demand measurement of detailed state variables. Accordingly, Fuji Electric developed a high-accuracy anomaly diagnosis technology by multivariate statistical process control (MSPC) for batch processes. This raises great expectations for improvements in the management level to prevent the manufacture of defective products and to conduct preventive maintenance of equipment in the manufacturing process.

3.1 MSPC

Statistical process control refers to a technology that uses a statistical technique to monitor process operating conditions. The aim is to prevent the manufacture of products that do not meet the specifications in order to improve productivity. Univariate statistical process control (USPC), which has long been in wide use, is a technology to diagnose anomalies by setting the upper and lower limits of the control limit for process variables that have an influence on quality. However, it is prone to falsely detecting anomalies when the width between the upper and lower limits is too narrow and is not able to detect anomalies when the width is too wide.

Meanwhile, MSPC takes the correlations between

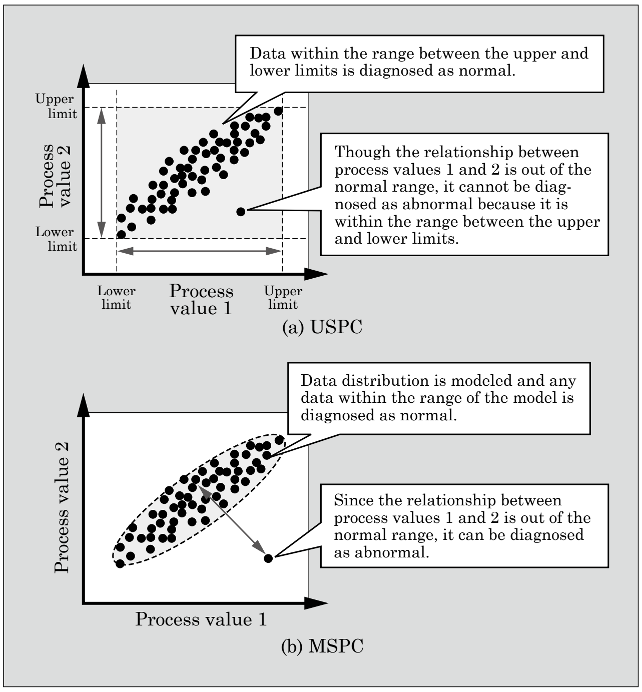

Fig.2 Difference between USPC and MSPC in anomaly diagnosis

variables into account for diagnosis, rather than judging anomalies by simply using upper and lower limits (see Fig. 2). First, the data in the normal range are modeled by using the principal component analysis technique. The model is then used to define the elliptic range shown in Fig. 2(b) as the normal range. For diagnosis, judgment is made based on the degree of deviation between the values of the variable to be diagnosed and this normal range. In this way, MSPC can accurately detect anomalies that cannot be detected by USPC.

3.2 MSPC for batch processes

Generally in a batch process, the process values are not constant but the correlations between variables change in the middle of the process. Accordingly, applying MSPC as it is may cause anomalies to be buried in larger changes of correlations between variables during the progress of the process, which makes detection of those anomalies difficult. To deal with this problem, we have developed MSPC for batch processes. It is capable of accurately detecting small anomalies in a batch process by subtracting the standard profile (average batch process change) from the raw data of the batch process as shown in Fig. 3.

3.3 Application example

This section describes an example of applying the MSPC for batch processes to a refrigerated showcase used for selling perishables in convenience stores and supermarkets. Refrigerated showcases may break down due to frost formation in the hot and humid period in summer. If a showcase fails, it causes sig-

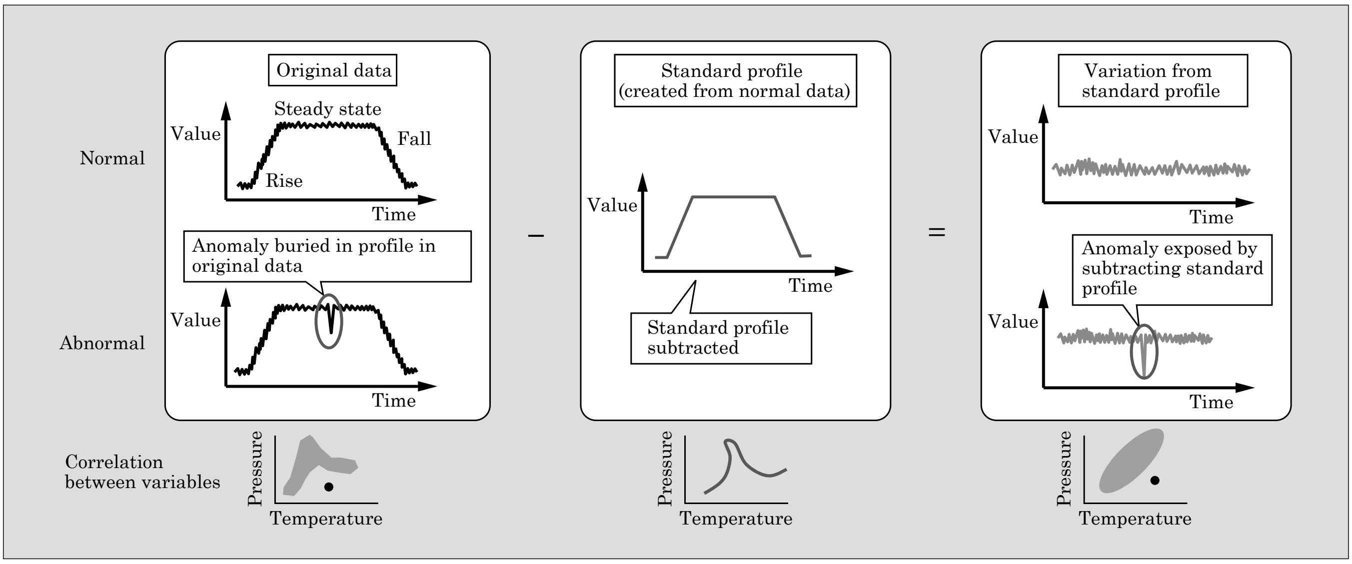

Fig.3 MSPC for batch processes

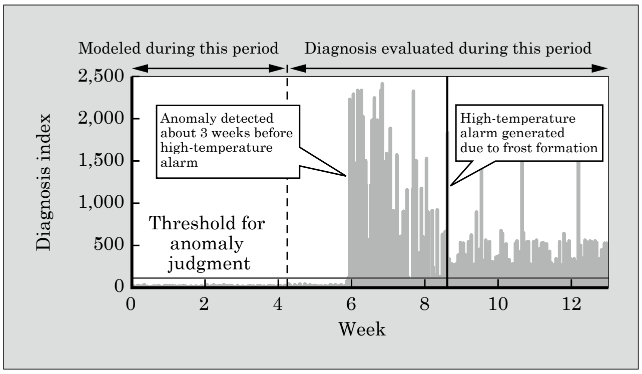

Fig.4 Example of application to refrigerated showcase

nificant losses to both the stores and consumers and needs to be predicted in advance so that measures can be taken. In refrigerated showcases, defrosting takes place at regular intervals and temperature and other data change periodically. This can be treated as a batch process.

Figure 4 shows an example of a refrigerated showcase in a real store. It was diagnosed by generating a high-temperature alarm caused by frost formation. Conventionally, frost could not be detected before an alarm was generated but, in this example, the diagnosis index rapidly increased about 3 weeks before the generation of the anomaly, which shows that a sign of an anomaly was clearly identified.

4. Anomaly Symptom Detection Based on Ensemble Prediction

Conventionally, for operating various plants, USPC is generally employed. In it, the upper and lower limits are set for the variable to be monitored to use as the basis for generating an alarm when any anomaly occurs. The operator runs the plant while predicting any anomaly in advance so that no alarm will be generated. For prediction, a common method is to check the trends of the variable to be monitored. Then, the upper and lower limits for the alarm are set in 2 stages, for the main alarm and pre-alarm as the preliminary stage, in order to monitor for a pre-alarm. For example, the upper limit can be set as the pre-alarm and the upper upper limit as the main alarm. This will configure operations to prevent the main alarm from being generated when the upper limit threshold value is exceeded, thereby ensuring safe operation of the plant. This method, however, had a problem that a pre-alarm did not necessarily guarantee the main alarm would be generated. It also had the problem that setting a low threshold value for the pre-alarm caused more cases of false detection.

In order to solve this problem, Fuji Electric has developed a technology for predicting anomaly generation by building a prediction model for the plant from the large volume of data accumulated. We are using it to predict changes in the monitored object. The main features are as follows:

(a) Capability of predicting changes in the monitored object after a pre-alarm
(b) A high detection rate maintained by prediction even with a higher pre-alarm threshold value
(c) A longer time margin allowed between the prediction and generation of the main alarm

4.1 Ensemble prediction

As techniques for building a prediction model from numerical data, statistical models and neural networks are often used. Statistical models include multiple regression and partial least squares models. With these models, the prediction accuracy greatly depends on the choice and preparation of the data used for creating a model, choice of variables used as the explanatory variables and the values of various parameters used when the model is created. Conventionally, a trial and error

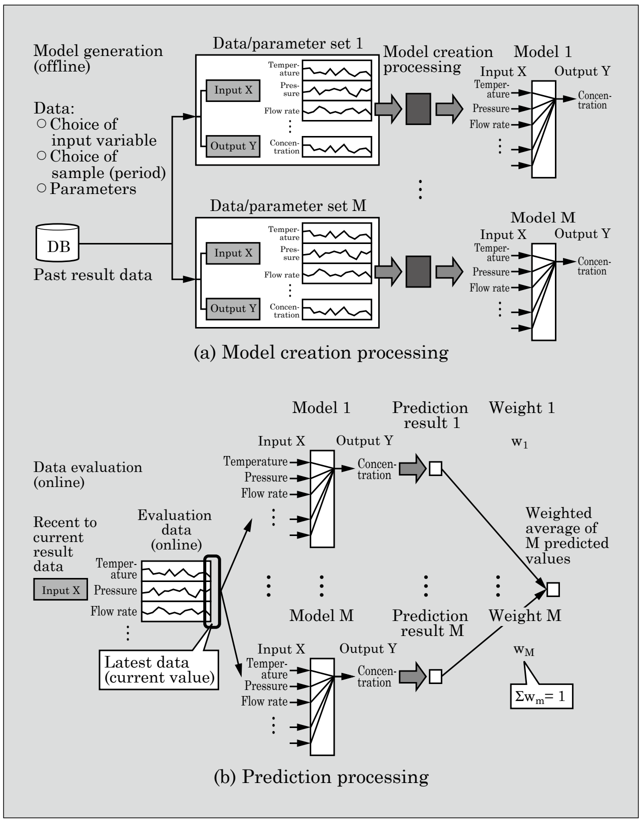

Fig.5 Outline of ensemble prediction

process was necessary to appropriately choose and set the conditions of model creation. In addition, the prediction accuracy greatly varied at times depending on the prediction model.

In order to deal with these problems, we have developed "ensemble prediction," in which the weighted average of outputs of multiple models with different learning data and parameters is used as the result of prediction (see Fig. 5). Ensemble prediction, which equalizes the prediction accuracy variation between the respective models, allows accurate prediction.

4.2 Application example

Figure 6 shows an example of predicting variables of the monitored object of a certain incineration plant.

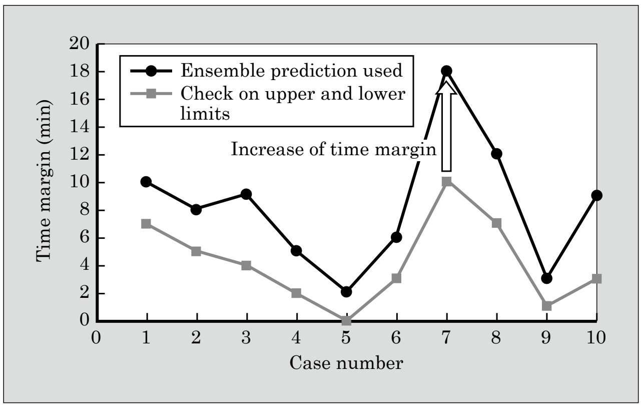

Fig.6 Example of application to incineration plant

The case number in the figure indicates that for an event with an actual anomaly generated. A time margin is a time period between detection of a sign of an anomaly and generation of the actual anomaly. In all cases of an anomaly generated, ensemble prediction shows a longer time margin, which indicates that the manager can deal with any anomaly generated with more time in advance.

5. Technology for Visualizing Potential Energy Savings via Formula Manipulation Optimization

Fuji Electric is working on popularizing energy management systems (EMSs) for measuring the amounts of energy consumption and supply of plants and offices to optimize equipment operation. The key to doing this is prior assessment including that of the energy-saving effect produced by introducing a system and payout time. Introduction of an EMS requires measuring equipment and related management systems, including systems for data management, monitoring, optimization, and the initial investment often becomes high. Accordingly, it is extremely important to make sure that energy reduction worth the initial investment cost is feasible, but accurately estimating it before the actual introduction is not easy.

To solve this problem, Fuji Electric has developed the world's first tool to visualize potential energy savings. It works by comparing the most energy-saving operable range of the equipment with the conventional operation based on the energy efficiency characteristic formula for the equipment.

5.1 Formula manipulation

Formula manipulation is a technology for automatically solving mathematical problems by using algorithms such as the quantifier elimination method. This is a method of transforming a polynomial with quantifiers expressed as a first-order predicate logical formula into an equivalent polynomial with all of the variables with quantifiers eliminated by repeating formula transformation and substitution. To visualize potential energy savings, the quantifier elimination method is used to transform a set of formulae, such as the characteristic formula and operation limiting conditions for the energy supply equipment, into a set of formulae only for the load and supply cost. This makes it possible to visualize the relationship between the load and supply cost.

5.2 Potential energy savings visualization tool

The potential energy savings visualization tool determines the operable range that satisfies the limiting conditions. It does this by using formula manipulation to solve the energy efficiency characteristics and operation limiting conditions such as the upper and lower limits of output for the intended energy supply equip-

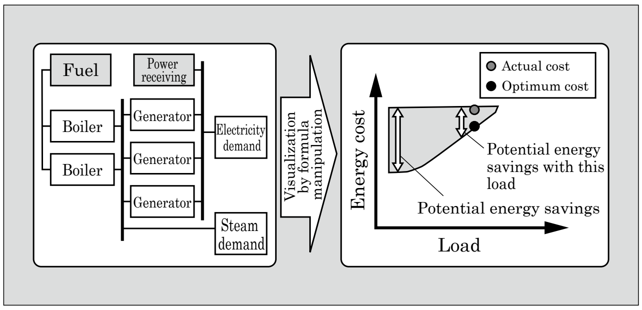

Fig.7 Outline of visualization of potential energy savings

ment. It then compares it with the conventional operation for visualizing the potential energy savings.

The operable range of the equipment here does not mean a simple total of the upper limits of the equipment capacity. It is the operable range that satisfies the limiting conditions of operation of the equipment including the upper and lower limits of output mentioned above and energy supply and demand balance. As shown in Fig. 7, the operable range can be plotted by the relationship between the load and cost of energy to supply to the load. The lowest side of the operable range indicates operation with the minimum cost and the potential energy savings can be easily grasped by looking at the difference from the actual operation.

5.3 Application example

Figure 8 shows an example of visualization by using formula manipulation for equipment that covers an air-conditioning load with 4 centrifugal chillers. As shown in Fig. 8(b), the 4 centrifugal chillers have different energy efficiency characteristics and upper and lower limits of output. Efficient operation is difficult with simple equalized output distribution or quantity control.

Figure 8(c) shows a result of visualization. The horizontal axis represents the overall air-conditioning load L and the vertical axis the total received power P and the filled in portions in the figure indicate operable ranges. Portions with a narrow width of the received power along the vertical axis against the load along the horizontal axis indicate that the degree of freedom of operation is small there. For example, with a 100 kW load, the operable ranges represented by 3 lines correspond to centrifugal chillers 1, 2 and 4 and, above all, centrifugal chiller 1 is shown to provide the highest efficiency and receives the lowest power. The figure shows that, in a portion with a wide width of the received power along the vertical axis against the load such as with a 400 kW load, multiple pieces of equipment are combined for operation and the received power may greatly vary depending on the output distribution of the respective pieces of equipment. The symbol ● indicates conventional operation and ▲ the state of optimum operation corresponding to conventional operation, and the difference between them is the potential energy saving. In an area with a larger

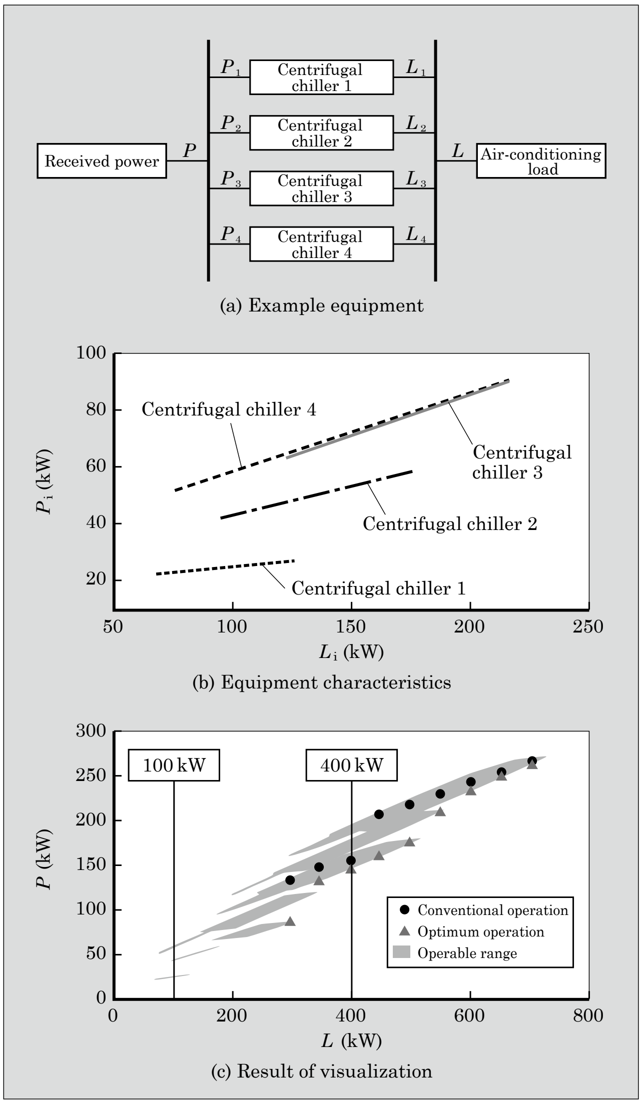

Fig.8 Example of application to centrifugal chiller equipment

difference between them, the energy-saving effect of optimization is larger.

In this way, the economic effect produced by introducing an EMS in various operating conditions can be grasped in advance by using the potential energy savings visualization tool. In addition, by applying this tool to an existing EMS, the optimality of the state of operation of the EMS can be checked and the certainty of the prior conditions including equipment characteristics can be verified. Furthermore, when replacement or addition of energy supply equipment is under consideration, the energy-saving effect of replacement or addition can be quantitatively understood in advance.

6. Postscript

This paper has given an overall picture of mathematical application technologies related to IoT solutions. It has also presented, as the latest mathematical application technologies, anomaly diagnosis technology for batch processing, anomaly symptom detection based on ensemble prediction and a technology for visualizing potential energy savings via formula manipulation optimization. In the future, we intend to continue to work on the establishment of technologies with a higher degree of perfection through application to real plants and create new customer value.

References

(1) Kurotani, K. et al. Current Status and Prospects of Measurement and Control Technologies. FUJI ELECTRIC REVIEW. 2012, vol.58, no.1, p.2-8.

(2) Matsui, T. et al. Data Analysis Technology in Plant Contrtol. FUJI ELECTRIC REVIEW. 2014, vol.60, no.1, p.21-26.

Fuji Electric

Innovating Energy Technology