Recent Optimization Techniques and Applications to Customer Solutions

Shinji Kitagawa
Michio Takenaka
Yoshikazu Fukuyama

1. Introduction

Companies operate by setting goals in various business fields, and then taking action to achieve those goals. Optimization techniques are one way to obtain operation (decision making) that will, to the extent possible, approach goals that have been set in response to a given problem. As a result, solutions such as designs for minimal operating cost, optimal product quality, smallest device size and the like can be realized.

The development of optimization techniques began during World War II, when they were used to optimize the trajectory of missiles. Subsequently, mathematical programming has been developed to realize optimization through the application of mathematical techniques. Additionally, the optimization technique of meta-heuristics (MH), which imitates physical phenomena and the evolution of living organisms, has been developed since the 1970s. Furthermore, Fuji Electric has begun working to develop an optimization technique that is superior to conventional meta-heuristics. In the past, new optimization techniques had been developed in each era in order to realize customer solutions. But now, those optimization techniques are dated and new solutions are being realized.

This paper introduces recent optimization techniques and their application to customer solutions.

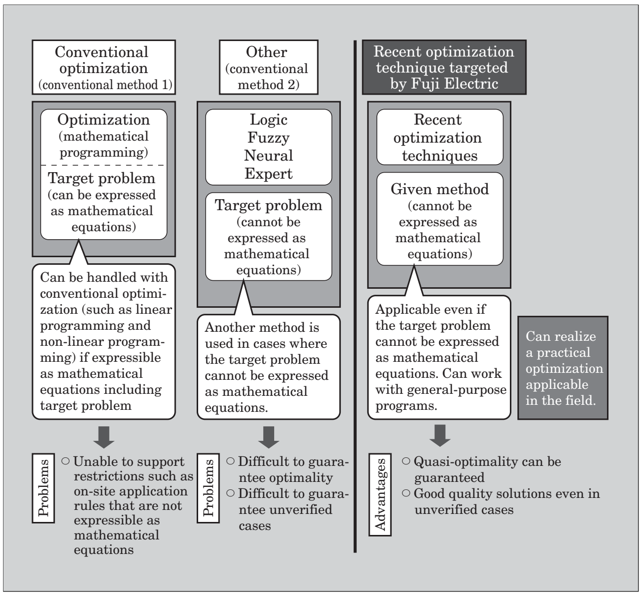
2. Recent Optimization Techniques

2.1 Problems with conventional decision-making techniques and characteristics of requested techniques

When making a decision in order to achieve a certain goal, mathematical optimization techniques such as mathematical programming have been utilized in cases where the target problem can be expressed as a mathematical equation (conventional technique 1 in Fig. 1). On the other hand, if the target problem cannot be expressed in a mathematical equation, neural networks, fuzzy logic, expert systems and other decision-making techniques have been utilized (conventional technique 2 in Fig. 1). In cases where the mathematical expression is only an approximation, practical use of conventional technique 1 was potentially difficult. The problem with conventional technique 2 is the difficulty in guaranteeing the generation of good quality solutions for cases that have not been verified. Moreover, analytical calculation for each target problem is often possible with a general-purpose program (such as a finite element package, for example). However, as shown in Fig. 1, with conventional technique 1, it is not possible to isolate the target problem from the optimization program, and it was difficult to coordinate use with an independent general-purpose program in order to analyze the target problem.

Therefore, in consideration of crude onsite operating constraints such as the constraint of only being capable of expressing if-then rules, and in consideration of other factors such as the coordination with an independent general-purpose program, a technique that can obtain good solutions — even in cases that have not been verified — is required. As a recent optimization technique capable of responding to these types of needs, Fuji Electric is researching and devel-

Fig.1 Conventional decision making techniques and recent optimization techniques



oping a new optimization technique that uses meta-heuristics and the stability theory for nonlinear systems as described below.

2.2 Meta-heuristics

Meta-heuristics is a technique that uses simulations of the behaviors involved in physical phenomena and living organisms to realize a general-purpose optimization search framework that does not depend on the target problem.

Various meta-heuristic techniques exist, including genetic algorithms (GA), simulated annealing (SA), tabu search (TS) and particle swarm optimization (PSO) (see Table 1).

GA uses chromosomes to express a problem and searches for a solution with alternations of generations using natural selection and genetic operations such as cross-over and mutation. SA searches for solutions by modeling the gradual decrease in molecular vibration when liquid steel is cooled and solidified into a solid state and a minimum energy state is reached. TS realizes effective searches by searching for only new solutions and prohibiting (tabu) a return to any solutions that had been searched for previously. PSO searches for solutions by modeling the condition in which a swarm, such as a flock of migrating birds, behaves skillfully as a group or a decision making process in which personal information is shared skillfully among a group. Here, the mixed-integer nonlinear optimization problem for PSO is a problem of finding the combination of optimal values for state variables that contain both discrete variables (such as the tap values of a transformer, for example) and continuous values (the output of an electric power generator, for example). A typical optimization problem considers both discrete and continuous variables, and often becomes a mixed-integer nonlinear optimization problem. Fuji Electric has successfully applied PSO for the first time in the world in the fields of power and energy.

The recent PSO technique, which is applicable to various fields, is summarized below. PSO was developed in 1995 at Purdue University by Professor Eberhart et al. PSO is a solution search technique in which the particle has become a swarm. There are two techniques behind the development of PSO. The first is the technique of modeling the behavior of a swarm, such as a herd of animals, and the second is cognitive psychology. The behavior of a flock of migrating birds can be expressed simply as a combination of vectors, i.e. a vector pointing toward the center of the flock, a vector that maintains a constant distance with neighboring birds, and a vector pointing in the direction of the flock's flight path. It is known that the behavior of the flock can be modeled with extreme accuracy by adding an appropriate random number to these three vectors. Moreover, in the field of cognitive psychology, it is known that decisions are made based on a person's own experience and the experiences of people. Professor Eberhart developed PSO, which is more efficient for searching than conventional meta-heuristics, by preparing multiple solution search points (corresponding to multiple birds), and as shown in Equation (1), searching for a solution based on a personal best

Table 1 Comparison of meta-heuristic techniques

	GA	SA	TS	PSO	Recent optimization technique using stability theory for nonlinear systems
Development period	1970s	1983	1989	1995	2003
Target problem	Combinatorial optimization problem	Combinatorial optimization problem	Combinatorial optimization problem	Continuous optimization problem , Mixed-integer nonlinear optimization problem	Combinatorial optimization problem, Continuous optimization problem, Mixed-integer nonlinear optimization problem
State variable	Discrete variable	Discrete variable	Discrete variable	Continuous variable, Discrete variable	Continuous variable, Discrete variable
No. of search points	Multi-point search	Single point search	Single point search	Multi-point search	Single point search
Solution guarantee	Guaranteed that all solutions will be in a favorable direction	Guaranteed that global minimum will be obtained	No mathematical guarantee	Trial mathematical analysis of search behavior is underway.	Able to guarantee with a search method based on mathematical theory (logic is being formulated)
Run time	Medium	Long	Short	Short	Medium
Features	In recent years, application efficacy for multi-objective optimization problems has been under review.	A good quality solution can be obtained, but it will require a long amount of time.	Good quality solutions can be obtained for combinatorial optimization problems in a shorter amount of time than with GA or SA	Good quality solutions can be obtained within a short amount of time for mixed-integer nonlinear optimization problems, for which solutions were difficult to obtain with conventional methods.	The most efficient and accurate solution can be obtained for large-scale problems.

(Pbest) point (corresponding to one's personal experience) having the best evaluation among individual search points and a group best (Gbest) point (corresponding to experience that includes other people's experiences) having the best evaluation among the swarm of search points, while changing the direction of the search in the direction of the present search direction composite vector.

Next search direction = Present search direction
+ Pbest direction + Gbest direction ················· (1)

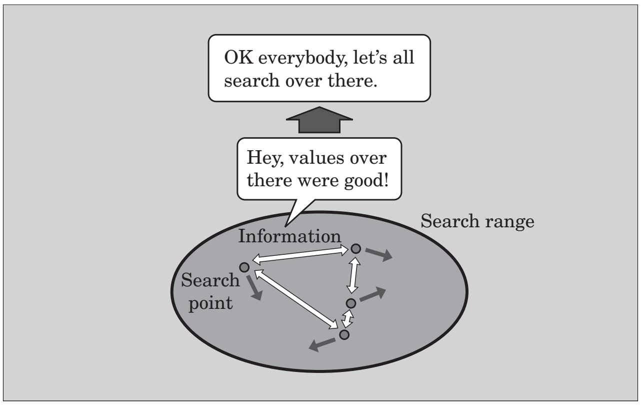
In actuality, a weighting factor (function) is applied to each term on the right side of the equation, and the present search direction is initially set to a random value. Consequently, in the search space, multiple birds (search points) search for the optimal solution while exchanging information of favorably evaluated search points (Fig. 2).

Fuji Electric has added improvements to this recent PSO technology to realize solutions that use a constricted factor approach, hybrid PSO, adaptive PSO, etc.

2.3 New optimization techniques using stability theory for non-linear systems

Meta-heuristics has an advantage in that a good quality solution can be obtained even in cases when the target problem cannot be expressed as an equation or it is necessary to use general-purpose software. However, for practical purposes, the probability of producing a good quality solution decreases for large-scale problems. Rather than optimization within a small range, as is often said, end users require "total optimization" over a broad range that may expand from one building to an entire factory and then to an entire production operation. In the future it will be necessary to deal with even larger scale problems. Moreover, since techniques such as GA, SA and PSO are stochastic methods, there is no guarantee that a good quality solution will always be obtained, and moreover, a different solution may be obtained each time. If the same solution were to be obtained each time, the degree of freedom would decrease and the probability of obtaining a good solution would also

Fig.2 Concept of particle swarm optimization



decrease. For this reason, it is necessary to carefully tune a search for the purpose of practical utility. Fuji Electric is developing a new optimization method based on stability theory for nonlinear systems that will compensate for these types of deficiencies in meta-heuristics and will always yield a good quality solution for large-scale problems (Table 1). An overview of this method is described below.

Mathematical programming has been developed as a way to find local minima by calculating the slope of the objective function of each search point in an optimization process (① in Fig. 3). With this method, however, it is not possible to escape from a local minimum to find the global minimum located in another valley (② in Fig. 3). In order to overcome this disadvantage of mathematical programming, meta-heuristics were developed as a method for escaping from local minima by imitating the alternation of generations of living organisms and the behavior of swarms.

Here, in looking at the shape of the objective function in slightly greater detail, it can be seen that after reaching a local minimum, traveling through the lowest part of a mountain ridge is an effective way to reach the next valley. Similarly, once a local minimum has been obtained, the surrounding local minima can

Fig.3 Concept of the escape from local minima

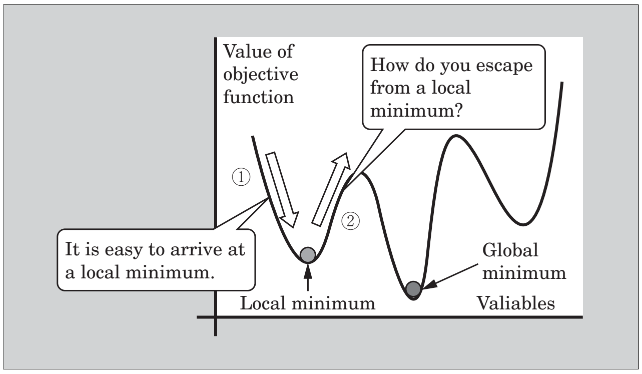
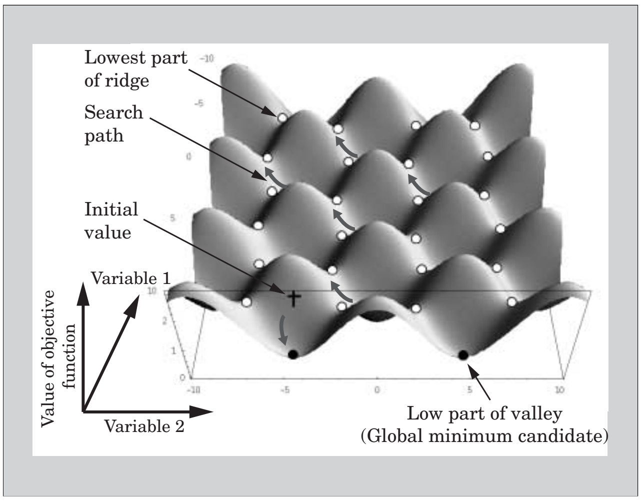


Fig.4 Efficient search method for local minima



be obtained in a minimum amount of time by repeatedly traveling through the lowest part of mountain ridges to reach the local minima in neighboring valleys (Fig. 4). The optimal solution can be found as the best solution among local minima obtained within a given amount of time (solution closest to the global minimum). This type of method was proposed by Professor Chiang et al. of Cornell University, and has the disadvantage of requiring considerable run time.

Improving on this method, Fuji Electric is developing a method that uses continuation methods and eigenvalue analysis to quickly find the lowest point on a ridge and then find the local minima within a short amount of time. It has been verified that use of this method enables the global minimum to be obtained within a short amount of time, even in the case of large-scale and complex objective functions. Although this method is still in its research phase, practical R&D is advancing toward the realization of applications in various fields.

3. Solutions Using Recent Optimization Techniques

Here, the sensor diagnostic function in the optimal operation of an energy plant is presented as an example of a solution that uses optimization techniques.

Figure 5 shows the system configuration of an energy plant optimal operation system. The sensor diagnostic function is executed at the stage before data is input to each function of the optimal operating system as a historical data management function. Sensor measurement data acquired via a LAN are automatically corrected for measurement errors, and if the correction amount is large, the sensor is specified as an "abnormally measuring sensor" and the operator is notified. The sensor diagnostic function basically consists of the following two functions.

3.1 Sensor measurement correction function

For practical use, even if the sensor information contains measurement errors, various functions of the optimal operation system must realize continuous operation and output appropriate results. In order to continuously output appropriate results, a sensor measurement correction function operates to automatically correct sensor measurement values such that the error between a sensor measurement value and the plant simulator calculation result is minimized. This problem can be formalized as the following optimization problem.

State variables:

Plant simulator input values (various types of fuel, load values, etc.)

Objective function:

Minimization of the error between measured and calculated values

In other words, the combination of plant simulator input values for which the value of the objective function is a minimum, is obtained, and the sensor measurement value is automatically corrected based on the plant simulator calculation results at that time. Realization of this function is based on PSO, which is one of the meta-heuristic techniques.

3.2 "Abnormally measuring sensor" specification function

In cases where the correction by the abovementioned function is large, this "abnormally measuring sensor" specification function specifies the sensor thought to be the cause of that abnormality. This problem can be formalized as the following combinatorial optimization problem.

State variables:

Combination of normal measurement and abnormal measurement sensor states

Objective function:

Minimization of the error between normal measurement values and calculated values, and maximization of the probability that a "normally measuring sensor" will exist

In other words, the error between a measured value from a "normally measuring sensor" and a plant simulator calculation result, the number of "normally measuring sensors" that exist, and the like, are judged

Fig.5 Optimal operation of an energy plant having a sensor diagnostic function

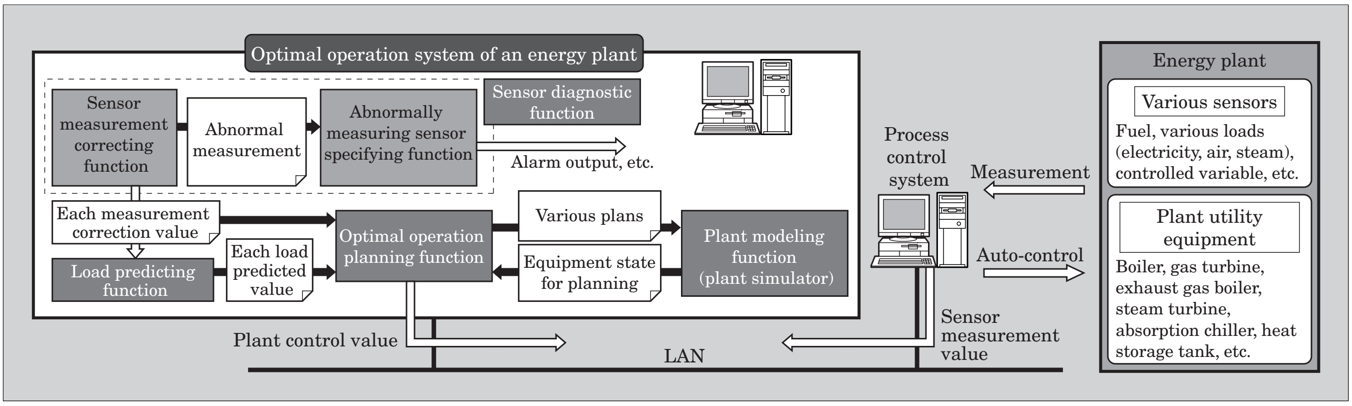
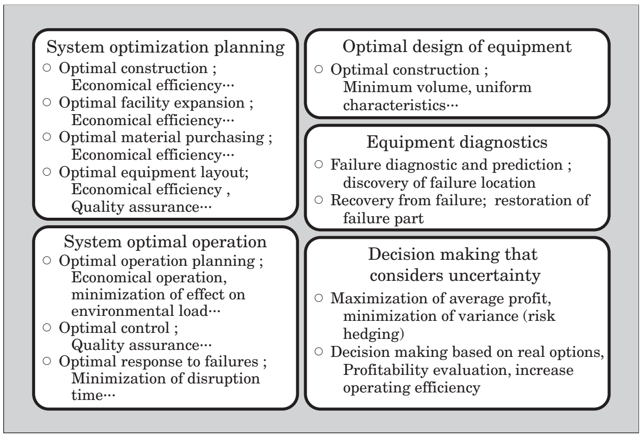


Fig.6 Examples of application areas of recent optimization techniques



in a comprehensive manner, and the combination of sensor states that yield the best objective function value is obtained, and within that combination, sensors in an abnormal measuring state are specified as "abnormally measuring sensors." Moreover, using the same method as with the function of section 3.1, correction of the sensor measurement value based on the plant simulator calculation result may be realized at the same time as the best objective function value is obtained.

These functions utilize the results of an external program known as a plant simulator, and therefore, could not be realized with conventional mathematical programming. Moreover, these functions require meta-heuristic techniques and are realized based on PSO. With these types of functions, maintenance costs can be decreased by transferring from time-based maintenance (TBM) that performs regular maintenance to conditional-based maintenance (CBM) that performs maintenance on an as-needed basis. Fuji Electric is supplying the FeTOP and PowerCC as energy plant optimal operation tools that incorporate these types of sensor diagnostic functions.

Figure 6 lists examples of the application areas of these recent optimization techniques.

4. Conclusion

This paper has discussed recent optimization techniques being developed by Fuji Electric and presented examples of applications to solutions. In the future, Fuji Electric intends to advance optimization techniques further and to realize customer solutions.

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