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Optimal Production Scheduling by Integer Form of Population-Based Incremental Learning with Initial Probability Matrix Setting Methods and a Practical Production Simulator

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***Abstract*— This paper proposes an optimal production scheduling method using a practical production simulator and integer form of population-based incremental learning (IF-PBIL) with two initial probability matrix setting methods. There are three parameters for decision variables in a target factory. It is necessary to optimize these three parameters at the same time in order to evaluate them. Moreover, IF-PBIL is one of the cooperative metaheuristics and determines integer values based on probability values and generates solutions. Initial integer values are determined by equal probability values, and various solutions are generated. Hence, there is a possibility that it is difficult to search high-quality solutions from initial stages of the search. Furthermore, since the production simulator requires long execution time, the execution number of the production simulator should be reduced as much as possible. In order to tackle the challenge, the proposed method applies two initial probability matrix setting methods. It is confirmed that the proposed method can search high-quality solutions from initial stages of the search and can reduce the production costs with the fewer execution number of the production simulator using actual factory data of a polishing process of an assembly processing factory.**

***Keywords*— optimal production scheduling, production simulator, integer form of population-based incremental learning, initial probability matrix setting methods, carbon neutrality**

I. INTRODUCTION

In production scheduling researches, many studies have been conducted based on an ideal mathematical formulation such as job-shop scheduling problems (JSPs) in order to minimize production time [1]. At the 26th session of the Conference of the Parties to the United Nations Framework Convention on Climate Change (COP26) in 2021, parties were asked to take ambitious actions to meet objectives of reducing global carbon dioxide emissions to net zero around mid-century [2]. Up to now, production scheduling problems considering environmental loads have been proposed by adding minimization of energy consumption and $\mathrm{CO_2}$ emissions to the mathematical formulations of the problems [3-8].

In practical production factories, a production scheduling tool is utilized to generate a production factory model and production schedules because each practical production factory has different production facilities. Various parameters such as production ratios at production lines are set in the production scheduling tool. These parameters are optimization parameters at the practical production factories. However, there is a gap between parameters of JSP and parameters of the practical production factories because optimization parameters of JSP are only processing orders of operations for each machine. Therefore, in order to generate production schedules for the practical production factories, it is necessary to optimize various parameters of the practical production factories in the production scheduling tool although they are usually determined at the practical production factories. The current production scheduling tool can truly simulate the production factories. However, in order to consider environmental loads such as reducing $\mathrm{CO_2}$ emissions, it is necessary to add functions to the production scheduling tool so that the tool can evaluate indices such as energy consumption. Furthermore, there are many constraints that are difficult to express using mathematical equations at the practical production factories. Therefore, it is natural to treat the production simulator as a black box considering environmental loads. Hence, optimal production scheduling should be treated as a black box optimization problem. Parameters of the practical production factories should be optimized by inputting parameters such as the production ratios at production lines to the black box and outputting the production schedule and environmental index evaluation such as energy consumption from the black box. Therefore, since an applied optimization method must find a high-quality solution only with solutions and their objective function values, it is necessary to apply evolutionary computation methods instead of mathematical programming to the black box optimization problem.

The target practical production factory in this paper has three decision variables: production ratios and production orders at production lines, and production start time of products. In order to optimize the three parameters, it is necessary to predetermine the production ratios and the production orders at production lines before determining production start time of products. In addition, in order to determine the production orders at production lines, it is necessary to predetermine the production ratios at production lines and the production start time of products. Furthermore, in order to determine the production ratios at production lines, it is necessary to predetermine the production orders at production lines and the production start time of products. Therefore, it is necessary to optimize these three parameters simultaneously. In order to treat the optimization problem, the production ratio optimization problem should be set as a primal problem, the production order optimization problem should be set as a subproblem, and the production start time optimization problem should be set as a sub-subproblem. Hence, the optimization problem has three-layer hierarchical structure as shown in Figure 1, and the algorithm has the triple nested loops. Therefore, there is a possibility that the number of objective function evaluation is enormous.

Integer form of Population-Based Incremental Learning (IF-PBIL) [9] has been verified to be effective for various combinatorial optimization problems [10][11]. Therefore, it is expected to be effective for applying IF-PBIL to the optimal production scheduling. IF-PBIL is one of the cooperative metaheuristics. It determines integer values based on probability values and generates solutions during search processes. Initial integer values are determined by equal probability values, and various solutions are generated. Hence, it is difficult to search high-quality solutions from initial stages of the search and quality of solutions is gradually getting higher. Therefore, there is a possibility that the number of objective function evaluation is huge in order to search high-quality solutions. In order to tackle the challenge, the probability values of the probability matrix can be changed to certain values so that high-quality solutions can be generated from initial stages of the search.

The production simulator set as the black box considering environmental loads can calculate production costs using energy consumption based on machine operating statuses. In the practical production factories, various production parameters such as the production ratios and the production orders at production lines, and the production start time of products are utilized as decision variables of the optimization problem. Therefore, it is necessary to set the production parameters in the simulator and the parameters should be optimized by truly simulating the practical production factories responding to changes in parameters. Consequently, the production simulator considering environmental loads is utilized as a digital twin that can truly simulate the practical production factories. The authors have already developed the production simulator considering environmental loads (production simulator) [12]. However, since the production simulator requires long execution time, it is necessary to minimize the number of the production simulator execution, namely the number of objective function evaluation.

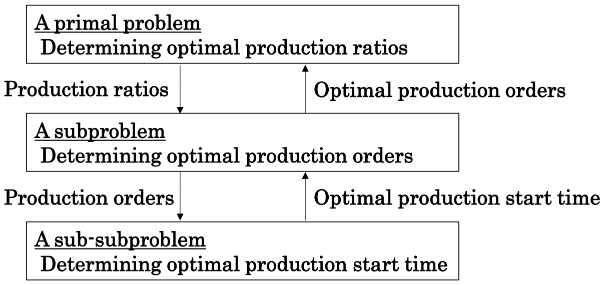


Fig. 1. An overview of the target optimization problem structure.

This paper proposes an optimal production scheduling method by IF-PBIL with initial probability setting methods and a production simulator considering environmental loads. Decision variables of the target optimization problem are production ratios at production lines, production orders at production lines, and production start time of products. If IF-PBIL is applied to the optimization problem, the enormous number of objective function evaluation must be required. Moreover, the production simulator requires long execution time and the execution number of the production simulator should be reduced as much as possible. In order to tackle the challenge, the proposed method applies initial probability matrix setting methods for the initial probability matrices of IF-PBIL. The initial probability matrix setting methods are applied to production ratio optimization and production start time optimization. An initial probability matrix for production ratios at production lines is generated by linear programming. An initial probability matrix for production start time of products is generated considering high electricity price intervals and working overtime intervals. Effectiveness of the proposed method is confirmed by comparing with the IF-PBIL with equal probability values in an initial probability matrix. It is confirmed that the proposed method can search high-quality solutions from initial stages of the search by the initial probability matrix setting methods and can generate solutions to reduce the production costs with the small number of objective function evaluation.

II. FORMULATION OF OPTIMAL PRODUCTION SCHEDULING USING THE PRODUCTION SIMULATOR

A. The Target Problem

In this paper, a polishing process of an assembly processing factory is modeled. There are various production lines that can produce same products in the process. These production lines have different production equipment. Therefore, production lines have different energy consumption, production time, and setup time to produce a product. It is possible to reduce production costs by setting appropriate parameters such as production ratios and production orders at production lines. Furthermore, an electricity unit price at each hour is different in each electricity utility. In addition, labor costs are higher by overtime. Consequently, it is possible to reduce production costs by setting appropriate parameters such as the production start time of products. Hence, decision variables in the target factory are the production ratios and the production orders at production lines, and the production start time of products.

B. The Production Simulator

In this paper, the practical production simulator developed by Mitsubishi Electric Corporation is utilized [12]. This simulator sets appropriate production parameters such as labor costs, production equipment, production capacity and energy consumption of each equipment. By inputting a production schedule and an equipment operation schedule, it is possible to calculate a production cost based on three indices: productivity, energy efficiency, and environmental loads.

C. *Formulation of an Optimal Production Scheduling problem*

(1) Decision variables

The decision variables are the production ratios of the jth product at the i th production line x_{ij} ($x_{ij} \in \mathbb{N}_1 : i = 1, \ldots, N_L, j = 1, \ldots, N_P$), the production orders of the j th product at the i th production line y_{ij} ($y_{ij} \in \mathbb{N}_2 : i = 1, \ldots, N_L, j = 1, \ldots, N_{Pi}$), and the production start time of the jth product at the ith production line z_{ij} ($z_{ij} \in \mathbb{N}_2$). $\mathbb{N}_1$ and $\mathbb{N}_2$ are natural numbers. N_L is the number of production lines. N_P is the number of products. N_{Pi} is the number of produced products at the ith production line.

(2) Objective function

A production cost is calculated in the objective function with three indices: productivity, energy efficiency, and environmental loads using the following equation.

$$\min(w_1 \times Pro + w_2 \times Ene + w_3 \times Env) + Penalty \qquad (1)$$

where, Pro is a term of productivity, Ene is a term of energy efficiency, Env is a term of environmental loads, w_1, w_2, and w_3 are weighting coefficients ($w_1 + w_2 + w_3 = 1$), $Penalty$ is a penalty function value that is corresponding to on-time delivery violation.

(3) Constraints

The constraints are expressed in a production scheduling tool in practical production factories, and it is difficult to formulate them mathematically. Therefore, they are calculated in the production simulator, which is a black box.

III. A PRACTICAL PRODUCTION SIMULATOR AND INTEGER FORM OF POPULATION-BASED INCREMENTAL LEARNING WITH AN INITIAL PROBABILITY MATRIX SETTING METHOD FOR OPTIMAL PRODUCTION SCHEDULING

A. *Overview of Integer Form of Population-Based Incremental Learning*

IF-PBIL is an expanded method of PBIL [14]. This method utilizes a probability matrix of probability values expressing occurrence of each integer value. Equations used for initialization and update equations are shown below.

$$P_{ij}^{iter} = \frac{1}{N_{CI}} \; (i = 1, \ldots, N_{CI}, j = 1, \ldots, N_D) \qquad (2)$$

$$P_{ij}^{iter+1} = P_{ij}^{iter} + \varepsilon \left(i = B_j^{iter}, j = 1, \ldots, N_D\right) \qquad (3)$$

$$P_{ij}^{iter+1} = P_{ij}^{iter+1} \times (1.0 - MUT\_SHIFT) + random(0.0 \; or \; 1.0) \times MUT\_SHIFT \qquad (4)$$

where P_{ij}^{iter} is a probability value of an integer value that can be the ith solution of the jth decision variable at iteration $iter$, N_{CI} is the number of integer values that are solution candidates, N_D is the number of decision variables, ε is a learning constant, B_j^{iter} is an integer value index of the best solution of the jth decision variable at iteration $iter$, MUT_SHIFT is the mutation amount, $random(0.0 \; or \; 1.0)$ is 0.0 or 1.0 selected by a uniform random number.

Since sum of the probability values expressing occurrence of each integer value of a column for each decision variable in the probability matrix is not 1.0 after applying equations (3) and (4), normalization is performed.

B. *An initial probability matrix setting method for optimal production ratios by IF-PBIL*

1) A method for determining the high-quality production ratios of all target products at production lines by linear programming: As described in Introduction, the optimization problem structure has the triple loop structure because three parameters are utilized as decision variables in this paper. It is necessary to optimize these three parameters at the same time by determining the production ratios and the production orders at production lines, and the production start time of products in this order. Therefore, there is a possibility that the number of objective function evaluation is enormous. Moreover, IF-PBIL has been verified to be effective for various combinatorial optimization problems [10][11]. There is a possibility that the number of objective function evaluation is huge in order to search high-quality solutions because various solutions are generated in initial stages of a search. Therefore, this optimization problem with IF-PBIL needs enormous number of objective function evaluation. In order to solve this challenge, it is necessary to generate high-quality solutions from initial stages of the search. Therefore, the initial probability matrix can be changed using high-quality solutions instead of using equal probability values.

The high-quality production ratios at production lines are determined by linear programming, where total production time for all products is the shortest. In the linear programming problem, production efficiency at each production line, the number of products, production time of one product, setup time, and break time are considered. The problem of determining the high-quality production ratios formulated as a linear programming problem is shown below.

a) Decision variables: r_{ij} is the production ratios of the jth product at the ith production line (every 10%).

b) Objective function: It can be expressed with the objective function of minimizing the production time for all products as follows:

$$min\, f(r_{ij}) = \sum_{j=1}^{N_P} \left(N_j \sum_{i=1}^{N_L} (r_{ij} \times T_{ij}) \right) \qquad (5)$$

where N_P is the number of products, N_j is the number of jth product, N_L is the number of production lines, T_{ij} is production time of jth product at the ith production line.

c) Constraints

i) Production ratio constraint: The sum of the production ratios of products is 1.0.

$$\sum_{i=1}^{N_L} r_{ij} = 1 \;\; (j = 1, \ldots, N_P) \qquad (6)$$

ii) Available production time constraint: The sum of production time at each production line must be within the available production time.

$$\sum_{j=1}^{N_P}\left(N_j \times r_{ij} \times T_{ij}\right) \leq TPT \times \alpha \quad (i = 1, \dots, N_L) \tag{7}$$

where TPT is available production time allowed for production from the earliest start time to the delivery time, α is fixed parameter.

iii) Non-negative production ratio constraint: The production ratios of products at production lines must be greater than or equal to 0.

$$r_{ij} \geq 0 \ \ (i = 1, \dots, N_L, j = 1, \dots, N_P) \tag{8}$$

2) An initial probability matrix setting method for production ratios at production lines: Using the high-quality production ratios at production lines obtained by linear programming, the initial probability values for integer values in the initial probability matrix to the high-quality production ratios at production lines are increased while the initial probability values for other integer values are decreased. Using the initial probability matrix setting method, solutions close to the high-quality production ratios at production lines can be obtained from initial stages of a search. In other words, it is possible to search high-quality solutions with a small number of objective function evaluation. As described above, there is a possibility that the number of objective function evaluation is enormous by applying IF-PBIL. However, the initial probability matrix setting method can solve the challenge.

In addition, after applying equations (3) and (4), normalization is applied because the sum of the probability values of each decision variable in the probability matrix are not 1.0. Furthermore, the sum of the integer values of the production ratios of products at production lines obtained by IF-PBIL is modified to become 100%.

C. An initial probability matrix setting method for optimal production start time by IF-PBIL

1) A method for determining high-quality production start time of a product: Considering electricity price at each hour and costs for working overtime, a certain point obtained by exchanging the costs to the point for each hour is set as the hour point. An upper hour point that allows production to begin for products is set using the hour point. The production start time of each product is determined using the sum of the hour point for all the production hours of the product without exceeding the current upper hour point times all the production hours. However, when the sum of the hour point exceeds the current upper hour point times all the production hours, the current upper hour point raises one step. The high-quality production start time of a product is determined by the following algorithm.

Step.1 The hour points are sorted in ascending order to generate an hour point vector.

Step.2 The minimum index of the hour point vector ($n = 1$) is set as an initial upper hour point. The current producing product p is set to 1.

Step.3 If $p = 1$, hours from the earliest time to be able to start to the delivery time are set as the available production hours. If $p \neq 1$, hours from production finished time of the $(p-1)$ th determined product to the delivery time are set as available production hours of the pth product. If the available production hours are longer than the production hours of the pth product, go to Step 4. If not, go to Step 5.

Step.4 If the sum of the hour point of the pth product does not exceed the current upper hour point times all the production hours during the available production hours of the p th product, the production start time of the p th product is determined with the earliest time to be able to start, $p = p + 1$, and return to Step 3. If the sum of the hour point of the pth product exceeds the current upper hour point times all the production hours, go to Step 5. If the current producing product p reaches the number of all products P, go to Step 6.

Step.5 If the index of the hour point vector n do not reach the maximum index of the hour point vector, N, $n = n + 1$, $p = 1$, and return to Step 3. If the index of the hour point vector n reaches N, the production start time of each product is determined from the earliest time to be able to start in order without float time, and go to Step.6.

Step.6 A combination of the production start time of each determined product at the target production line is determined as the high-quality production start time.

The initial probability matrix of IF-PBIL is set using the high-quality production start time of each product in the same way described in section III.B.

D. Production orders by the enumeration method

Practically, IF-PBIL can be applied to the optimal production orders at the production lines. However, in order to reduce the number of objective function evaluation, the production orders at production lines are determined by the enumeration method instead of applying IF-PBIL. All combinations of the production orders at production lines are enumerated and total setup time is calculated when produced products are changed. The production orders at production lines are determined as a combination with the shortest total setup time.

E. An optimal production scheduling algorithm using a practical production simulator and IF-PBIL with initial probability matrix setting methods

In this paper, the current best solution for all the production ratios at production lines, production orders at production lines, and production start time of products is called the current global best production schedule. Moreover, the current best solution for certain production ratios, certain production orders, and production start time when only optimizing the production start time is called the current local best production schedule.

Step.1 *Setting the initial probability matrix for the production ratios at production lines:* The initial probability matrix setting method for the production ratios described in section III.B is applied to generate the initial probability matrix for the production ratios. Iteration for production ratios, t_r is set to 1.

Step.2 *Generation of solutions for the production ratios:* M_r solutions (individuals) of the production ratios are generated based on the current probability matrix of the production ratios. Solution number for production ratios, m_r is set to 1.

Step.3 *Determination of the production orders:* Using the m_rth solution of the production ratios, the production orders at production lines are determined by the enumeration method described in section III.D.

Step.4 *Optimization of production start time:* Optimal production start time of each product at each production line corresponding to the m_r th solution of production ratios generated at Step.2 and the production orders determined at Step.3 are determined by the following procedures.

Step.4.1 *Setting the initial probability matrix for the production start time of products:* The initial probability matrix setting method for the production start time described in Section III.C is applied to generate the initial probability matrix for the production start time based on the m_rth solution of production ratios and the production orders for all production lines. Iteration for production start time, t_{st} is set to 1.

Step.4.2 *Generation of solutions for the production start time:* Solutions of the production start time of each product at each production line are generated based on the current probability matrix of the production start time. M_{st} solutions of the production start time for all production lines (individuals) are determined by combining the solutions for production lines.

Step.4.3 *Calculation of production costs of production schedules:* M_{st} production schedules (the m_rth solution of production ratios, a solution of production orders for all production lines, and M_{st} solutions of production start time) are input to the production simulator, and the production simulator calculates production cost for M_{st} production schedules using (1). A solution of the production start time with the lowest production cost among M_{st} production schedules is determined as the current best production start time.

Step.4.4 *Update and mutation of the probability matrix of production start time:* Based on the current best production start time, the probability matrix of production start time is updated using (3), and mutation is performed using (4).

Step.4.5 *Determination of the current local best production schedule for the m_rth solution:* If $t_{st} = 1$, the m_rth solution of the production ratios, a solution of the production orders, and the current best production start time obtained at Step.4.3 are determined as the current local best production schedule for the m_rth solution. If $t_{st} \neq 1$, if the production cost of the current best production schedule obtained at Step.4.3 is less than the production cost of the current local best production schedule for the m_rth solution, the current local best production schedule for the m_rth solution is updated.

Step.4.6 If t_{st} reaches the maximum iteration T_{st}, go to Step.5. If not, $t_{st} = t_{st} + 1$ and go to Step.4.2.

Step.5 *Determination of the best production ratios at iteration t_r:* If $m_r = 1$, the m_rth solution of the production ratios is set as the current best production ratios. A production cost of the current local best production schedule for the m_r th solution is set as a production cost of the current best production ratios.

If $m_r \neq 1$, if the production cost of the current local best production schedule for the m_r th solution is less than the cost of the current best production ratios, the production cost of the current best production ratios is updated.

Step.6 If m_r reaches M_r, go to Step.7. Otherwise, $m_r = m_r + 1$ and go to Step.3.

Step.7 *Update and mutation of the probability matrix of production ratios:* Based on the current best production ratios, the probability matrix of production ratios is updated using (3), and mutation is performed using (4).

Step.8 *Determination of the current global best production schedule:* If $t_r = 1$ and $m_r = 1$, the current local best production schedule is determined as the current global best production schedule. If $t_r \neq 1$ or $m_r \neq 1$, the production cost of the current local best production schedule is less than that of the current global best production schedule, the current global best production schedule is updated.

Step.9 If t_r reaches the maximum iteration T_r, go to Step.10. Otherwise, $t_r = t_r + 1$ and go to Step.2.

Step.10 The current best global production schedule is output as the final production schedule.

IV. SIMULATIONS

A. Simulation Conditions

The proposed method is verified using one-day scheduling and one-week scheduling of a polishing process of an assembly processing factory with production lines capable of producing products simultaneously. The production costs of the following three methods are compared for one-day scheduling.

i) The proposed method

ii) A comparative method 1: *e*qual probability values in the initial probability matrix of IF-PBIL is utilized.

iii) A comparative method 2: production ratios at production lines obtained by linear programming explained in subsection B in section III, production orders at production lines obtained by the enumeration method explained in subsection D in section III, and production start time of products obtained by the proposed method for determining high-quality production start time of a product explained in subsection C in section III, are utilized.

Moreover, the production costs of the proposed method and the comparative method 2 are compared for one-week scheduling.

Parameters of IF-PBIL are shown below. The parameters are determined by pre-simulations.

1) Common parameters for production ratios and production start time:

The number of iterations: 10, The number of individuals: 10, ε: 0.1, MUT_PROB: 0.01, MUT_SHIFT: 0.01

2) A parameter for an initial probability matrix setting method for production ratios at production lines:

α: 0.7, initial probability values in the initial probability matrix for the production ratios obtained by linear programming: 0.6, initial probability values in the initial probability matrix for other production ratios: 0.04 (equal allocation of 0.4 to all other ten production ratios)

3) Other parameters:

a) Parameters for the objective function:

$w_1 = 0.333, w_2 = 0.333, w_3 = 0.333$

b) Parameters for one-day scheduling

the number of products: 4 (Product (1), (2), (3), and (4)),
the number of production lines: 4 (Line A, B, C, and D),
the number of trials: 30

c) Parameters for one-week scheduling

the number of products: 10,
the number of production lines: 3, the number of trials: 10

Simulation softwares are developed using gcc version 10.2.0 on an Intel core i9-10980XE (3.00GHz) PC

B. Simulation Results

1) Simulatiom results of one-day scheduling

Table 1 shows an average value and a standard deviation of the objective function values of the production schedules by the proposed method, an average value of the objective function values by the comparative method 1, and the objective function value of the comparative method 2. The average value of the objective function value of the proposed method is 49.26% ((0.66889 - 0.33940) / 0.66889 * 100) less than the objective function value of the comparative method 2. Figure 2 shows convergence characteristics through 30 trials (thin gray lines) and an average convergence characteristic (a thick red line) of the proposed method, an average convergence characteristic of the comparative method 1 (a thick blue broken line), and a solution of the comparative method 2 (a thick black dashed line). The proposed method can search high-quality solutions from the initial stages of the search, and an objective value of the production schedule with a worst objective function value is about 2 / 3 of it by the comparative method 2. It is necessary to obtain high-quality solutions with a small number of searches for the target optimization problem. Therefore, effectiveness of the initial probability matrix setting method is confirmed.

Table 2 shows high-quality production ratios obtained by linear programming. Table 3 shows the production ratios of the production schedule with the best objective function value through 30 trials by the proposed method. Different production ratios are expressed with thick numbers. Between the both production schedules, the way how each product is produced at a certain production line is almost same. Only the production ratios for producing each product are slightly different. Therefore, it is effective to generate an initial probability matrix of production ratios at production lines by linear programming.

TABLE I. AN AVERAGE VALUE AND A STANDARD DEVIATION OF THE OBJECTIVE FUNCTION VALUES OF THE PRODUCTION SCHEDULES BY THE PROPOSED METHOD, AN AVERAGE VALUE OF OBJECTIVE FUNCTION VALUES OF THE PRODUCTION SCHEDULES BY THE COMPARATIVE METHOD 1, AND AN OBJECTIVE FUNCTION VALUE BY THE COMPARATIVE METHOD 2 FOR ONE-DAY SCHEDULING

An ave. value of obj. func. of the opt. prod. schedules by the proposed method	A std. of obj. func. values of the opt. prod. schedules by the proposed method	An ave. value of obj. func. of the opt. prod. schedules by the comparative method 1	An obj. Func. value by the comparative method 2
0.33940	0.09176	0.71295	0.66889

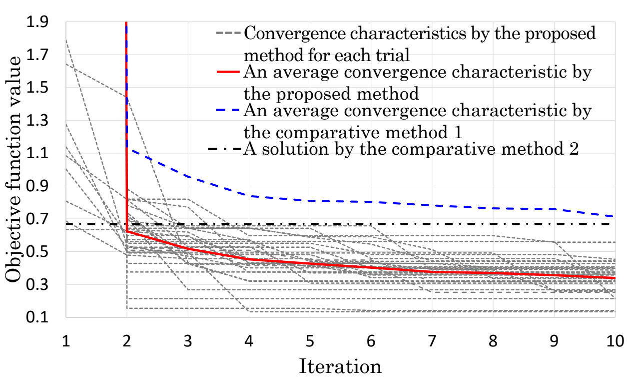


Fig. 2. Convergence characteristics by the proposed method and the comparative method 1 and 2 for one-day scheduling.

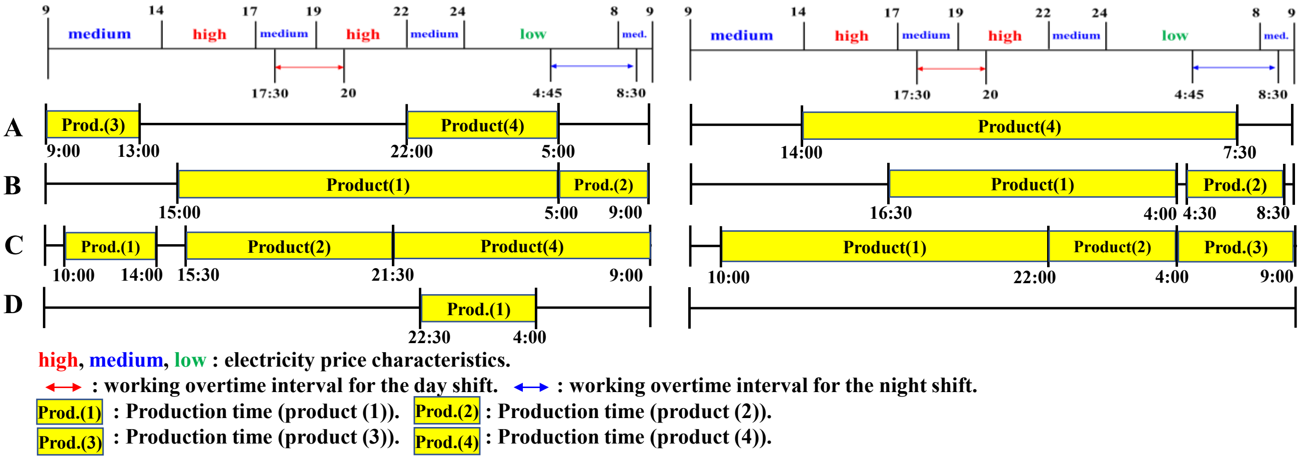
TABLE II. THE HIGH-QUALITY PRODUCTION RATIOS OF THE FOUR PRODUCTS AT THE FOUR PRODUCTION LINES BY LINEAR PROGRAMMING FOR ONE-DAY SCHEDULING

	Product (1)	Product (2)	Product (3)	Product (4)
Line A	0.0	0.0	**0.0**	**1.0**
Line B	**0.5**	0.2	0.0	0.0
Line C	**0.5**	0.8	**1.0**	**0.0**
Line D	**0.0**	0.0	0.0	0.0

TABLE III. THE PRODUCTION RATIOS OF THE PRODUCTION SCHEDULE OF THE FOUR PRODUCTS AT THE FOUR PRODUCTION LINES BY THE PROPOSED METHOD FOR ONE-DAY SCHEDULING

	Product (1)	Product (2)	Product (3)	Product (4)
Line A	0.0	0.0	**1.0**	**0.4**
Line B	**0.6**	0.2	0.0	0.0
Line C	**0.2**	0.8	**0.0**	**0.6**
Line D	**0.2**	0.0	0.0	0.0

Figure 3 shows the production schedule with the best objective function value by the proposed method and a production schedule by the comparative method 2 with electricity price characteristics at each hour and working overtime intervals. In the production schedule by the comparative method 2, products are produced at almost all production time intervals at all production lines because products are tightly allocated to highly efficient production lines. Therefore, even if the algorithm in which products are allocated to each production line avoiding high electricity price intervals and working overtime intervals is utilized, almost all products are produced during high electricity price intervals and working overtime intervals as shown at the right-hand side of Fig.3. On the other hand, in the best production schedule by the proposed method, one product is produced at the production line D even if the production line D is not



(a) The best production schedule by the proposed method (b) The production schedule by the comparative method 2

Fig. 3. The best production schedule by the proposed method and the production schedule by the comparative method 2 with electricity price characteristics at each hour and working overtime intervals for one-day scheduling.

efficient. In the efficient production line A, two products are produced in short intervals completely avoiding high electricity price intervals and almost all working overtime intervals. Therefore, according to the optimization results, products are allocated not only to the efficient production lines but also to the inefficient production lines by optimizing the production ratios at production lines. Moreover, the production costs can be reduced avoiding high electricity price intervals and working overtime intervals by optimizing the production orders at production lines and the production start time of products. In other words, effectiveness of optimizing three parameters such as the production ratios and the production orders at production lines, and the production start time of products simultaneously is confirmed. Moreover, it is confirmed that high-quality production schedule can be generated with the small number of objective function evaluation using the proposed initial probability matrix setting method for the production start time of products.

2) *Simulatiom results of one-week scheduling*

Table 4 shows an average value and a standard deviation of the objective function values of the production schedules by the proposed method and the objective function value of comparative method 2. The average value of objective function by the proposed method is 32.53% less than the objective function value by the comparative method 2. Figure 2 shows convergence characteristics of all trials (thin gray lines) and an average convergence characteristic (a thick red line) by the proposed method, and a solution by the comparative method 2 (a thick black dashed line). The proposed method can search high-quality solutions from the initial stages of the search. In addition, all the final objective function values by the proposed method are better than the objective function value by the comparative method 2. According to the results, quality of the production schedules by the proposed method is higher than that of the production schedule by the comparative method 2.

V. CONCLUSIONS

This paper proposes an optimal production scheduling method by IF-PBIL with initial probability setting methods and a practical production simulator considering environmental loads. Decision variables of the target problem are production ratios at production lines, production orders at production lines, and production start time of products. Applying the IF-PBIL to the target problem, the enormous number of objective function evaluation is required essentially. Moreover, the production simulator requires long execution time and the execution number of the production simulator should be reduced as much as possible. In order to tackle the challenge, the proposed method applies two initial probability matrix setting methods. It is confirmed that the proposed method can generate high-quality solutions from initial stages of the search using the initial probability matrix setting method and can reduce the production costs with the fewer execution number of the production simulator.

As future works, the initial probability matrix setting method will be improved in order to generate better quality production schedules and other evolutionary computation methods will be applied.

TABLE IV. AN AVERAGE VALUE AND A STANDARD DEVIATION OF THE OBJECTIVE FUNCTION VALUES OF THE PRODUCTION SCHEDULES BY THE PROPOSED METHOD AND AN OBJECTIVE FUNCTION VALUE BY THE COMPARATIVE METHOD 2 FOR ONE-WEEK SCHEDULING

An ave. value of obj. func. of the opt. prod. schedules by the proposed method	A std. of obj. func. values of the opt. prod. schedules by the proposed method	An obj. Func. value by the comparative method 2
0.32757	0.07668	0.48547

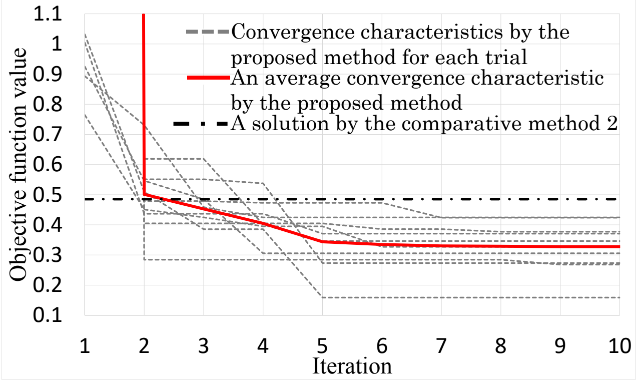


Fig. 4. Convergence characteristics by the proposed method for one-week scheduling.

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