**Paper:**

# Scheduling Algorithms Using Metaheuristics for Production Processes with Crane Interference

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**This paper proposes scheduling algorithms using metaheuristics for production processes in which cranes can interfere with each other. There are many production processes that involve cranes in manufacturing industry, such as in the steel industry, so a general purpose algorithm for this problem can be of practical use. The scheduling problem for this process is very complicated and difficult to solve because the cranes must avoid interfering with each other plus each machine has its own operational constraints. Although several algorithms have been proposed for a specific problem or small-scale problem, general purpose algorithms that can be solved in real time (about 30 minutes or less) in the company's production planning work have not been developed for large-scale problems. This paper develops some metaheuristic algorithms to obtain suboptimal solutions in a short time, and it confirms their effectiveness through computer experiments.**

**Keywords:** scheduling algorithm, production process, metaheuristics, crane interference, combinational optimization problem

## 1. Introduction

In recent years, the importance of scheduling systems has increased in order to cope with the diversification of products and short delivery times in the manufacturing industry. Scheduling problems in manufacturing are large, and complex, and there are constraints. It is therefore difficult to obtain the optimal solution within a practical time. In order to deal with the problems, various scheduling systems and ways of obtaining quasi-optimal solutions have been developed, such as [1–3]. This scheduling algorithm has been studied not only by universities but also by industries [4–6]. However, methods of solving the scheduling problem have not been proposed in the case of production processes with the following characteristics, although there are many in the manufacturing industry.

(a) Several machines are connected in multiple stages.

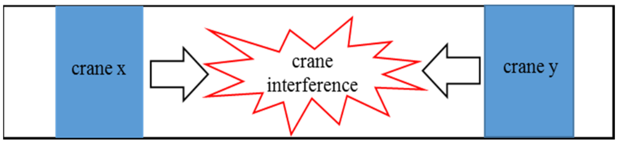


**Fig. 1.** Crane interference.

(b) The work-in-process (WIP) is conveyed between the machines by two or more overhead cranes.

Since it is necessary to avoid interference between cranes in addition to taking the operational constraints of each machine into consideration, it is difficult to obtain the optimal solution to such scheduling problems in real time. Several methods utilizing heuristics based on operational know-how or optimization theory have been studied.

For this scheduling problem, we propose a solution algorithm combining metaheuristics and operation simulation. In this paper, we describe previous research, our target process, a solution algorithm, and the results of a numerical experiment.

## 2. Previous Research

### 2.1. Scheduling Problem with Crane Interference

In a production process in which multiple cranes travel on a single track, the cranes interfere with each other's movements (**Fig. 1**), but they must avoid such interference. Still, by avoiding interference, delays in conveyance occur, and these may cause delays in the production schedule. To shorten the production time, a crane must be selected so that interference is avoided. In this paper, the product to be produced is referred to as the product, and the product being manufactured in the production process is referred to as the WIP.

Let us consider a case in which crane $x$ is at position A and crane $y$ is at position C. If crane $y$ is assigned to convey WIP $p$ from position A to position B and crane $x$ is assigned to convey WIP $q$ from position C to position D, crane interference will occur while the cranes are moving to their starting positions (**Fig. 2**). To avoid this, crane $x$'s

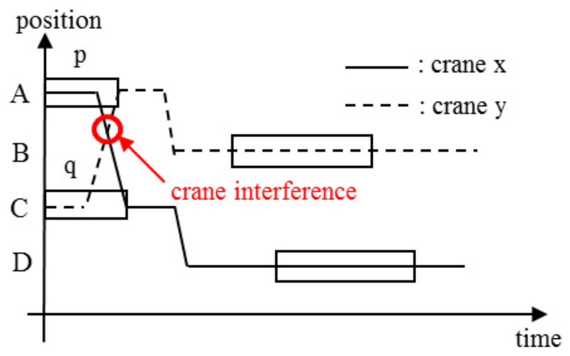


**Fig. 2.** Crane assignment where interference occurs.

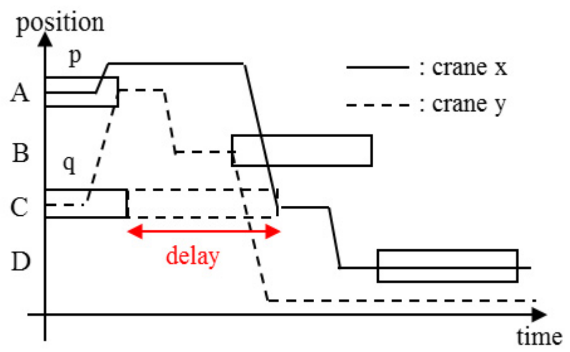


**Fig. 3.** Delay of starting time to avoid crane interference.

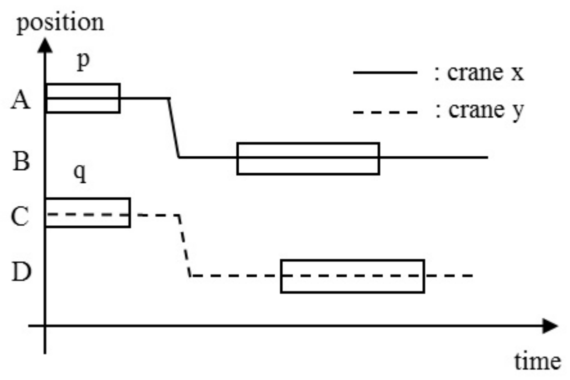


**Fig. 4.** Crane assignment without interference.

starting time is delayed (**Fig. 3**). However, if crane $x$ is assigned to convey WIP $p$ from position A to position B and crane $y$ is assigned to convey WIP $q$ from position C to position D, there will be no interference and no delay (**Fig. 4**).

## 2.2. Previous Research

Several ways of solving problem have been proposed. Imai et al. [7, 8] proposed a method using heuristics depending on the target process. In this method, crane interference is avoided according to the operation know-how table in which the discussion results of actual operations are tabulated. If the production process is different, it is necessary to change the operation know-how table. Therefore, the versatility of the solution is not high. Honda et al. [9] proposed a method to obtain an exact solution using the branch and bound method. This method can obtain an exact, optimal solution. However, on the other hand, there is a possibility that the solution will take a long time, as the scale of the problem becomes larger. Liu et al. [10] studied the refining scheduling problem involving two or more overhead travelling cranes with the non-collision constraint for handling material in a steel plant. They formulated this scheduling problem as a mixed integer programming model and developed the heuristic algorithms to obtain near-optimal solutions. Xie et al. [11] studied a scheduling problem involving enough two-category machines scheduled by a single crane in a batch annealing process in an iron and steel plant. They viewed the problem as a two-stage flexible flow shop with an additional transportation consideration and a proposed heuristic algorithm. Kim et al. [12] formulated the problem of scheduling quay cranes in port container terminals as mixed-integer programming. They proposed a branch and bound method to obtain the optimal solution to the quay cranes scheduling problem and a heuristic search algorithm. Moccia et al. [13] formulated the above problem as a vehicle routing problem and developed a branch-and-cut algorithm. Sammarra et al. [14] proposed a tabu search heuristic for the quay crane scheduling problem. Nguyen et al. [15] proposed a priority-based schedule construction procedure to generate quay crane schedules. Ng et al. [16] proposed a branch and bound algorithm to optimally solve a yard crane scheduling problem. Bierwirth et al. [17] proposed a method for assigning a quay crane used to load and unload containers onto a ship in port. In order to avoid interference among multiple quay cranes, they proposed a method in which container loading or unloading is assigned to quay cranes so that they move in a single direction. In this method, since the direction of travel of the quay crane is limited, operational efficiency may decrease. Many algorithms for solving the scheduling problems of "quay cranes in a port container terminal" have been proposed, but few algorithms for solving production process problems involving "overhead cranes in a production process" have been proposed. The equipment and method of transporting are different in a port container terminal and in a production process. We [18] proposed a method combining an enumeration tree search for crane assignment candidates and operation simulation. In this method, although it is possible to obtain feasible solutions in a short time, it is difficult to obtain a quasi-optimal solution with high accuracy, because the crane assignment depends on the assignment at the initial stage of the enumeration tree (the schedule at an early time), and it is not possible to search the entire solution space. Based on the above-mentioned literature survey results, only [18] is a prior study done on a solution algorithm for a production process with production machinery and transport equipment as in this research.

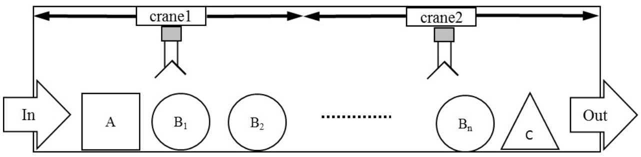


**Fig. 5.** Target process.

## 3. Target Process

The target process of this research is a production process with two cranes (**Fig. 5**). It is common not to limit the number of cranes to two. When there are two cranes, it is only necessary for one crane to avoid the other. When there three or more cranes, it is necessary to avoid interference with cranes on both sides. It is difficult to develop general-purpose algorithms that realize this. Therefore, algorithms for three or more cranes will be a future research subject.

In this paper, the product is carried in from the left side of **Fig. 5**, manufactured by some machines, and carried out from the right side. This process is modelled based on manufacturing processes that exist in many manufacturing industries, such as the steel industry.

### 3.1. Production Process

WIPs are manufactured through the following three processes.

(a) In the first process, WIPs are manufactured with machine A.

(b) In the second process, WIPs are manufactured with one or more machines, $B_1$ to $B_n$.

(c) In the third process, WIPs are manufactured with machine C.

### 3.2. Cranes

WIPs are conveyed between machines by either of two cranes. Both cranes can move from the left end to the right end in **Fig. 5**. When interference occurs from the positional relation of the cranes, the range of movement of both cranes is limited, and it is necessary to avoid interference. The crane conveyance speed and lifting/hanging time of each crane is fixed.

### 3.3. Objective Function and Constraints

The objective function is the minimization of the total time from the carrying-in to carrying-out of all products. The optimization problem considers the following eight constraints:

(a) During the production process, WIPs are not divided or integrated. Their weight does not increase or decrease.

(b) Each machine cannot manufacture more than two WIPs at the same time.

(c) The production machines, the production sequence and the production time in each machine are given for each product.

(d) WIPs are conveyed between machines with one of the two cranes.

(e) The two cranes must keep their distance from each other for safety.

(f) The operation starting time of the third process of each product is given. Delay of the operation starting time at the third process is avoided to the extent possible.

(g) The carry-in time of the first product is the operation starting time for the first process of that product.

(h) There is only one stock place in front of each machine. If the stock place of the next machine is full at the time the manufacturing at the current machine is completed, the WIP waits on the current machine or crane until the stock place of the next machine is available.

## 4. Formulation of the Problem

### 4.1. Notation

In order to formulate the problem, we use the following notations:

$t$ : current time
$U$ : set of products
$M$ : set of machines
$N_j$ : set of operations for product $j \in U$
$n_j$ : the number of operations for product $j$
$O_{ij}$ : $i$-th operation for product $j$ ($i = 1, \ldots, n_j$)
$OM_{ij}$ : machine for operation $O_{ij}$
$OT_{ij}$ : operation time for $O_{ij}$
$ST_{ij}$ : operation starting time of $O_{ij}$
$ET_{ij}$ : operation completion time of $O_{ij}$
$b_m$ : position of machine $m \in M$
$a_{ij}$ : position of $OM_{ij}$
$d$ : lifting or hanging time of crane
$\delta$ : minimum distance required for crane collision avoidance
$v$ : crane conveyance speed
$\gamma$ : delay time generated by interference
$CT(a,b)$ : crane conveyance time from position $a$ to position $b$

$$CT(a,b) = \begin{cases} \dfrac{|b-a|}{v} + 2d + \gamma & \text{(with lifting and hanging)} \\ \dfrac{|b-a|}{v} + \gamma & \text{(without lifting and hanging)} \end{cases}$$

$P_{kt}$ : position of crane $k$ at time $t$ ($k = 1, 2$)
$x_{ij}^m$ : 0–1 integer variable which is defined by

$$x_{ij}^m = \begin{cases} 1 : O_{ij} \text{ is operated at } m \\ 0 : \text{otherwise} \end{cases}$$

$X^m_{i_1 j_{1i}, i_2 j_2}$ : 0–1 integer variable which is defined by

$$X^m_{i_1 j_1, i_2 j_2} = \begin{cases} 1: O_{i_2 j_2} \text{ is operated after } O_{i_1 j_1} \text{ at } m \\ 0: \text{ otherwise} \end{cases}$$

$y^k_{ij}$ : 0–1 integer variable which is defined by

$$y^k_{ij} = \begin{cases} 1: \text{ crane } k \text{ conveys WIP completed } O_{ij} \\ 0: \text{ otherwise} \end{cases}$$

$Y^k_{ijt}$ : 0–1 integer variable which is defined by

$$Y^k_{ijt} = \begin{cases} 1: \text{ crane k conveys WIP completed } O_{ij} \text{ at } t \\ 0: \text{ otherwise} \end{cases}$$

$G$ : sufficiently large value

## 4.2. Formulation

The scheduling problem based on Section 3.3 is formulated as follows:

<Objective function>

$$\text{Minimize} \sum_{j \in U} \left( ET_{n_j, j} - ST_{1j} \right) \quad \dots\dots\dots \quad (1)$$

<Constraints>

$$\sum_{m \in M} x^m_{ij} = 1 \text{ for each } O_{ij}, \quad \dots\dots\dots \quad (2)$$

$$\sum_{O_{ij}} X^m_{i_1 j_1, ij} = x^m_{i_1 j_1} \text{ for each } m \text{ and } O_{i_1 j_1}, \quad \dots \quad (3)$$

$$\sum_{O_{ij}} X^m_{ij, i_2 j_2} = x^m_{i_2 j_2} \text{ for each } m \text{ and } O_{i_2 j_2}, \quad \dots \quad (4)$$

$$ST_{i_2 j_2} \geq ET_{i_1 j_1} + 1 - G(1 - X^m_{i_1 j_1, i_2 j_2})$$
$$\text{when } x^m_{i_1 j_1} = x^m_{i_2 j_2} = 1 \text{ for each } m, O_{i_1 j_1} \text{ and } O_{i_2 j_2}, \quad \dots\dots\dots \quad (5)$$

$$ST_{i_1 j_1} \geq ET_{i_2 j_2} + 1 - G X^m_{i_1 j_1, i_2 j_2}$$
$$\text{when } x^m_{i_1 j_1} = x^m_{i_2 j_2} = 1 \text{ for each } m, O_{i_1 j_1} \text{ and } O_{i_2 j_2}, \quad \dots\dots\dots \quad (6)$$

$$ET_{ij} \geq ST_{ij} + OT_{ij}, \text{ for each } O_{ij}, \quad \dots\dots \quad (7)$$

$$ST_{i+1,j} \geq ET_{ij} + CT(a_{ij}, a_{i+1,j}) \text{ for each } O_{ij}$$
$$\text{where } CT(a_{ij}, a_{i+1,j}) = \frac{|a_{i+1,j} - a_{ij}|}{v} + 2d + \gamma, \quad \dots\dots\dots \quad (8)$$

$$\sum_{k} y^k_{ij} = 1 \text{ for each } O_{ij}, \quad \dots\dots\dots \quad (9)$$

$$\sum_{O_{ij}} Y^k_{ijt} \leq 1 \text{ for each } k \text{ and } t, \quad \dots\dots\dots \quad (10)$$

$$\sum_{t = ET_{ij} - d + 1}^{ST_{i+1,j} + d - 1} Y^k_{ijt} \geq ST_{i+1,j} + 2d - ET_{ij}$$
$$-1 - G(1 - y^k_{ij}) \text{ for each } k \text{ and } O_{ij}, \quad (11)$$

**Table 1.** Description of objective function and constraints.

| No. | Description |
|---|---|
| (1) | Minimization of the total production time from starting time to the completion time of all products. |
| (2) | There is only one machine for each operation. |
| (3) | There is only one preceding operation on each machine. That is, WIPs are not divided. |
| (4) | There is only one subsequent operation on each machine. That is, WIPs are not integrated. |
| (5)<br>(6) | The relationship between the completion time of current operation and the starting time of subsequent operation at the same machine. |
| (7) | The relationship between operation starting time and completion time of WIP at each machine. |
| (8) | The relationship between the operation starting time at the next machine and the completion time at the current machine of WIP. |
| (9) | There is only one crane for each conveyance. |
| (10) | The crane cannot carry more than two WIPs at a time. |
| (11) | The crane which conveys WIP is occupied from the starting time to the completion time of conveyance. |
| (12) | Each WIP is operated at the installation place of the operation execution machine. |
| (13) | The relationship between the crane conveyance starting times, the crane conveyance starts position and the operation completion time. |
| (14) | The relationship between the crane conveyance completion times, the crane conveyance completion position and the operation starting time. |
| (15) | The range of the crane conveyance per unit time. |
| (16) | The distance between two cranes is $\delta$ or more. |

$$a_{ij} = \sum_{m \in M} b_m x^m_{ij} \text{ for each } O_{ij}, \quad \dots\dots\dots \quad (12)$$

$$P_{kt} = a_{ij} \text{ for } k \text{ satisfying } y^k_{ij} = 1 \text{ at } t = ET_{ij}, \text{ for each } O_{ij}, \quad \dots \quad (13)$$

$$P_{kt} = a_{i+1,j} \text{ for } k \text{ satisfying } y^k_{ij} = 1 \text{ at } t = ST_{t+1,j}, \text{ for each } O_{ij}, \quad . \quad (14)$$

$$P_{kt} + v \geq P_{k,t+1} \geq P_{kt} - v \text{ for each } k \text{ and } t, \quad . \quad (15)$$

$$P_{k+1,t} \geq P_{kt} + \delta, \quad \dots\dots\dots \quad (16)$$

$$P_{kt} \geq 0 \text{ for every } k \text{ and } t. \quad \dots\dots\dots \quad (17)$$

**Table 1** is a description of objective function and constraints.

## 5. Solution Algorithm

As described in Section 3, the production machines, the production sequence, and the production time for each machine are given, and the cranes are selectable in this problem. Therefore, the cranes are operated to minimize the total production time, from starting time to completion time, of all products. One crane carrying the WIP is chosen between two cranes, with the following aims.

(a) Crane operation that minimizes conveyance distance.

(b) Crane operation that minimizes operation delay due to machine conflict.

(c) Crane operation that minimizes operation delay due to crane interference avoidance.

### 5.1. Outline of Solution Algorithm

The proposed algorithm consists of two stages. The first stage is backward scheduling and the second stage is forward scheduling. In the backward scheduling, the time and the process are traced back from the operation starting time of the third step machine, and the operation starting and completion times of each machine are provisionally determined. At this stage, machine conflicts are avoided while crane interference and crane conflicts are not avoided. In forward scheduling, the crane operation and the operation starting and completion time of each machine are determined from the first step machine in the order of the provisionally determined operation starting time in backward scheduling to minimize the objective function value in Eq. (1). At this stage, machine conflicts, crane interference, and crane conflicts are avoided.

### 5.2. Algorithm for Backward Scheduling

Step 1: Initial setting
Set a set of products ($= U$).

Step 2: Backward scheduling
The product is taken out from $U$ in order of operation starting time of the third step machine later. The latest operation starting time ($LST_{ij}$) and the latest operation completion time ($LET_{ij}$) are provisionally calculated by Eqs. (18) and (19) while tracing back from the third step machine.

$$LST_{ij} = LET_{ij} - OT_{ij} \quad \text{(18)}$$

$$LET_{ij} = LST_{i+1,j} - CT(a_i, a_{i+1}) \quad \text{(19)}$$

When a machine conflict occurs, the operation starting and completion times are moved forward so that the machine conflict can be avoided. The moved operations are added to the competitive set ($= T$). Even if crane interference or conflict occurs, it is not taken into consideration. This product is removed from $U$.

Step 3: Terminal condition of backward scheduling
If $U$ becomes an empty set, go to Step 4. Otherwise, return to Step 2.

Step 4: Improvement of backward solution
If $T$ is not an empty set, the scheduling result is improved using a simple local search.

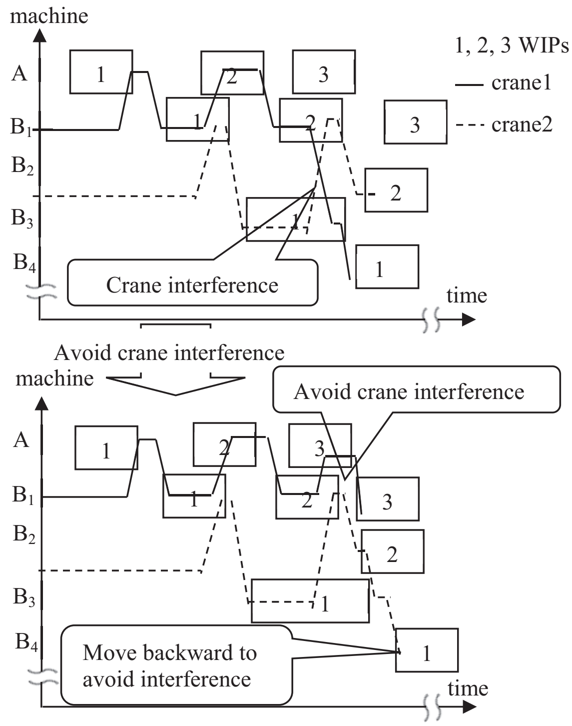


**Fig. 6.** Avoidance of crane interference.

### 5.3. Algorithm for Forward Scheduling

As described above, in forward scheduling, the crane operation and the operation starting and completion time of each machine are determined from the first step machine in the order of the provisionally determined operation starting time in backward scheduling to minimize the objective function value in Eq. (1). At this stage, the machine conflicts, crane interferences, and crane conflicts are avoided. When crane interference or machine conflict occurs, the starting and completion times of the crane and the machine are moved backward to avoid it (**Fig. 6**).

After the crane operation is determined, the operation starting and completion times of each machine are calculated using Eqs. (20) and (21).

$$RST_{ij} = ET_{i-1,j} + CT(a_{i-1}, a_i) \quad \text{(20)}$$

$$RET_{ij} = ST_{ij} + OT_{ij} \quad \text{(21)}$$

Therefore, the decision variable in the forward simulation is the assignment of crane 1 or crane 2 to crane conveyance. Let $Z$ be for the crane assignment vector. The elements of $Z$ are denoted as $z_1, z_2, \ldots, z_r$. $r$ is the number of crane conveyances. The elements of $Z$ are ordered in ascending order of the crane conveyance starting time (**Fig. 7**). In forward simulation, initial $Z$ is generated at random or by Diversification Generator (DG), it is improved and updated by metaheuristics, the starting time and completion time of each machine and crane are determined by operation simulation, and the objective function value in Eq. (1) is obtained by the operation simulation (**Fig. 8**).

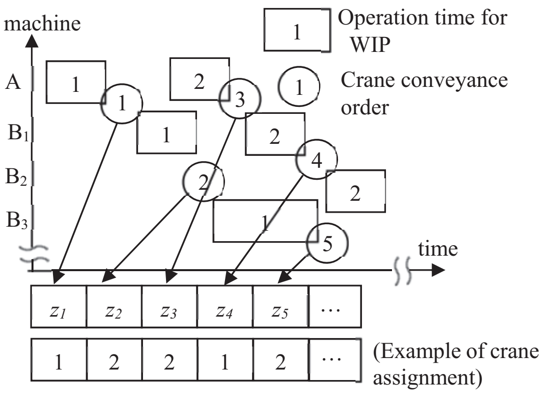


**Fig. 7.** Crane conveyance assignment.

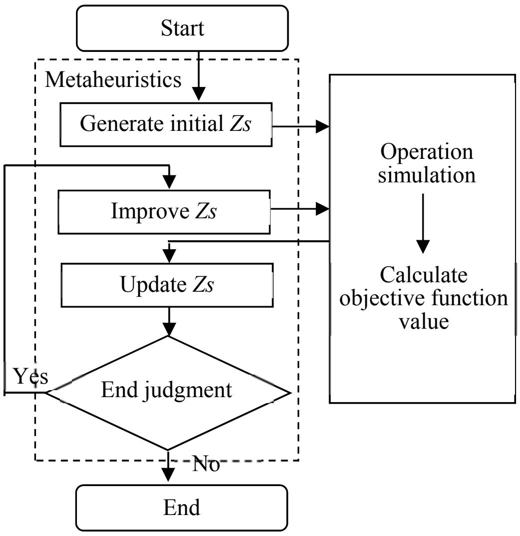


**Fig. 8.** Outline of forward simulation.

### 5.3.1. Algorithm for Generating Initial Individuals with DG

When using the genetic algorithm (GA) in metaheuristics, multiple initial solutions, i.e., the number of individuals, are required. The initial individuals of these solutions are generated randomly or by using DG. DG is a method of sequentially generating a new solution so that the Hamming distance becomes the maximum with respect to the basic solution [19]. The randomly generated initial individuals may not be uniformly generated and may be unevenly generated in the solution space. If the search starts from the initial individuals that are not evenly distributed in the solution space, there is a possibility that the solution space cannot be searched widely. By assigning crane conveyance to initial individuals using DG, we start searching from diversified initial individuals, and there is a possibility that the entire solution space can be searched widely. The algorithm of DG is shown below.

Step 1: Set initial value
Set $L$ for the number of individuals and $r$ for the number of crane conveyances. $q = 2$.

Step 2: Initialize $Z$
Initialize all elements of $Z$ with 1, meaning crane 1 is assigned.

Step 3: Generate $Z'$
Let $h = q$ and generate $z'_i$, which is an element of $Z'$, using Eq. (22).

$$z'_{1+hk} = 3 - z_{1+hk} (\text{for } k = 0, \ldots, \frac{r}{h}) \quad \ldots\ldots \quad (22)$$

Step 4: Generate 1–2 invert $Z''$ of $Z'$
Generate 1–2 invert $z''_i$ of $z'_i$ using Eq. (23). $z''_i$ is an element of $Z''$.

$$z''_i = 3 - z'_i \quad \ldots\ldots \quad (23)$$

Step 5: Generate right rotation shift $Z'''$ of $Z'$
When $h \geq 3$, generate $z'''_i$ by $u$-right rotation shifting to $z'_i$ (for $u = 1, 2, \ldots, h-1$).

Step 6: Generate left rotation shift $Z''''$ of $Z''$
When $h \geq 3$, generate $z''''_i$ by $u$-left rotation shifting to $z''_i$ (for $u = 1, 2, \ldots, h-1$).

Step 7: End judgment of generating initial individuals
When $Z$ is generated for $L$, it terminates. Otherwise, set $q = q + 1$ and return to Step 3.

### 5.3.2. Algorithm of Metaheuristics

In this research, we use GA and iterative local search (ILS) [20]. These algorithms are as follows. In the algorithms described below, $\tilde{Z}$ represents a set of LZ's.

<GA>
Step 1: Generate initial $\tilde{Z}$
Generate initial $\tilde{Z}$ randomly or by using DG. Let these $\tilde{Z}$ be parent $\tilde{Z}$.

Step 2: Operation simulation
Perform operation simulation for each initial $\tilde{Z}$. The operation starting and completion times of each machine and crane are determined. Calculate the objective function value.

Step 3: Generate new $\tilde{Z}$
A new $\tilde{Z}$ is generated by a two-point crossover method from the parent $\tilde{Z}$. Mutate with a certain probability for elements (crane assignments) of the new $\tilde{Z}$.

Step 4: Operation simulation
Perform the same operation simulation in Step 2 for each new $\tilde{Z}$ generated in Step 3.

Step 5: Update $\tilde{Z}$
Select $\tilde{Z}$ with small objective function values as the next generation parent individuals from the $2\tilde{Z}$ which is the sum of the parent $\tilde{Z}$ and the new $\tilde{Z}$.

Step 6: End judgement
When it repeats a pre-set number of times, it terminates. Let $Z$ with the smallest objective function value be the solution. Otherwise, return to Step 3.

<ILS>
ILS is a search method that iterates a simple local

search on a good solution obtained by a previous search plus random deformation. The algorithm of ILS is shown below.

Step 1: Generate initial $Z$

Obtain local optimal solution $Z$, as a result of a simple local search for the randomly determined initial solution. Set $Z_{seed} = Z$, $w = 1$. In the local search, the operation simulation is performed to calculate the objective function value. This also applies to the following local search.

Step 2: Local search

Choose a solution randomly from the $N^{(w)}(Z_{seed})$ and let the chosen solution be $Z'$. $N^{(w)}(Z_{seed})$ is the neighborhood $Z_{seed}$ of size $w$. Obtain local optimal solution $Z$, as a result of a simple local search for $Z'$.

Step 3: Update $Z$

If $f(Z) \leq f(Z_{seed})$, perform (a) with probability 1. If $f(Z) > f(Z_{seed})$, perform (a) with the transition probability (Eq. (24)). $f(Z)$ is the objective function value of $Z$. Otherwise, perform (b).

$$\text{transition probability} = e^{-\frac{f(Z)-f(Z_{seed})}{t}}$$

($t$ is a parameter) (24)

(a) Set $Z_{seed} = Z, w = 1$.
(b) $w = \min(w+1, w_{\max})$.

Step 4: End judgment

If the termination condition is satisfied, it terminates. Let $Z$ with the smallest objective function value be the solution. Otherwise, return to Step 2.

### 5.3.3. Operation Simulation

The important point of this algorithm is the avoidance of crane interference. First, we describe how the proposed algorithm can avoid crane interference. After that, we describe the operation simulation algorithm.

<Additional notation>

- $V$ : A set of operation in which a delay occurs in the operation time provisionally-determined by backward simulation.
- $s_{ij}$ : Crane conveyance starting time after $O_{ij}$
- $e_{ij}$ : Crane conveyance completion time before $O_{ij}$
- $s^*_{ij}$ : Crane conveyance starting time after $O_{ij}$ after avoiding crane interference
- $e^*_{ij}$ : Crane conveyance completion time before $O_{ij}$ after avoiding crane interference
- $a^*_{ij}$ : Crane conveyance starting position after $O_{ij}$ after avoiding crane interference
- $\varepsilon_{ij}$ : Delay time caused by operation conflict at $O_{ij}$
- $RST_{ij}$ : Starting time of $O_{ij}$ after updating delay time
- $RET_{ij}$ : Completion time of $O_{ij}$ after updating delay time

<Avoidance of crane interference>

To simplify the discussion, we assume the following.

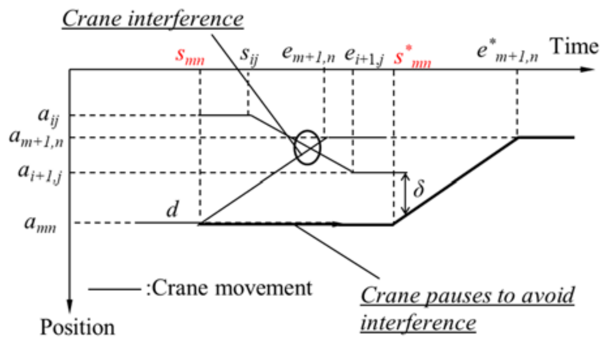


**Fig. 9.** Avoidance of crane interference (crane pauses).

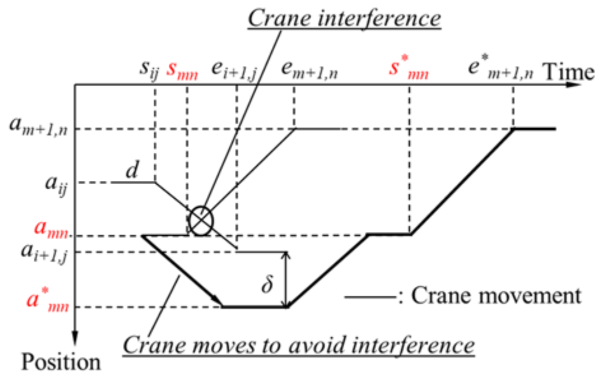


**Fig. 10.** Avoidance of crane interference (crane moves).

(a) Crane 1 conveys from $a_{ij}$ to $a_{i+1,j}$. Crane 2 conveys from $a_{mn}$ to $a_{m+1,n}$.

(b) The conveyance of crane 1 is determined. The conveyance of crane 2 to avoid interference with the crane 1 is considered.

(c) Crane interference is avoided before the conveyance starting time of the crane.

There are two cases depending on the position and movement of the crane to avoid interference of the crane.

Case 1: Pause the crane at its position (**Fig. 9**)

When Eq. (25) is satisfied, crane interference with the conveyance range of crane 1 is avoided at the conveyance starting position $a_{mn}$ of crane 2. Therefore, crane interference is avoided by pausing the conveyance of crane 2 until time $s^*_{mn}$ in Eq. (26) and shifting its starting time backward.

$$a_{mn} \geq a_{i+1,j} + \delta. \quad \ldots \ldots \ldots \quad (25)$$

$$s^*_{mn} = e_{i+1,j} + d - \frac{a_{mn} - (a_{i+1,j} + \delta)}{v}. \quad \ldots \quad (26)$$

Case 2: Moving the crane (**Fig. 10**)

When Eq. (27) is satisfied, crane interference with the conveyance range of crane 1 occurs at the conveyance starting position $a_{mn}$ of crane 2. Therefore, crane interference is avoided by moving crane 2 to $a^*_{mn}$ in Eq. (27)

and shifting its starting time to $s^*_{mn}$ in Eq. (28).

$$a_{mn} < a_{i+1,j} + \delta \quad (27)$$

$$a^*_{mn} = a_{i+1,j} + \delta \quad (28)$$

$$s^*_{mn} = e_{i+1,j} + d + \frac{a^*_{mn} - a_{mn}}{v} + d. \quad (29)$$

The algorithm of operation simulation is shown below.

Step 1: Set initial value
Pick one $Z$ that has not decided the crane schedule from $\tilde{Z}$. Set $q = 1$.

Step 2: Crane conveyance calculation
Calculate the start and completion of the crane conveyance for crane assignment $z_q$. Check whether there is interference with the other crane within the conveyance range of $z_q$. When the crane interferes, avoid it at Eqs. (25)–(29).

Step 3: Update the starting and completion time after the crane conveyance
Calculate the operation starting and completion time of the machine after $z_q$ in Eqs. (20) and (21). If a delay occurs in the operation time of the next machine, update the delay time below. Otherwise, go to Step 4. Furthermore, if the delay propagates to the subsequent machine for the product concerned, the delay time is updated for the subsequent machines as well. If the delay spreads to other products, the delays are updated in the same way for those products.

Step 3.1:
Store this operation of the machine in set $V$.

Step 3.2:
Pick one operation from $V$ in earlier order operation completion time. If there is a next machine, calculate the operation starting and completion time in Eqs. (30) and (31).

$$RST_{i+1,j} = RET_{ij} \quad (30)$$

$$RET_{i+1,j} = RST_{i+1,j} + OT_{i+1,j} + \varepsilon_{i+1,j} \quad (31)$$

Step 3.3:
If $RET_{i+1,j} > ET_{i+1,j}$, store the operation of the machine in set $V$. If there is a delay in the next operation in the same machine, store the next operation $V$.

Step 3.4:
If $V$ becomes an empty set, go to Step 4. Otherwise, return to Step 3.2.

Step 4: Check for the next crane conveyance in $Z$
Set $q = q + 1$. If $q <= r$ return to Step 2. Otherwise calculate objective function value in Eq. (32).

$$\text{Objective function value} = \sum_{j \in U} \left( RET_{n_j,j} - ST_{1j} \right) \quad (32)$$

Step 5: Check for the next $Z$
If there is $Z$ that has not decided the crane assignment in $\tilde{Z}$, return to Step 1.

**Table 2.** Operation time and machine position.

| Machine | A | $B_1$ | $B_2$ | $B_3$ | $B_4$ | $B_5$ | C |
|---|---|---|---|---|---|---|---|
| Operate time | 28 | 20 | 16 | 21 | 30 | 15 | 20 |
| Position | 20 | 35 | 55 | 80 | 120 | 150 | 220 |

## 6. Computer Experiments and Discussion

We solved the same scheduling problems using the proposed method (GA, GA + DG, ILS) and the method proposed in [18] (PR), and we compared the objective function values in Eq. (1) and the solving time. PR is a method combining an enumeration tree search of crane assignment candidates and operation simulation.

### 6.1. Computer Experiment Conditions

**Table 2** shows operation time and machine position from the left side in **Fig. 5**. The number of machines $B_n$ is set to 5. Many machines are installed on the left side in **Fig. 5** because there are few factory layouts in the manufacturing industry with machines installed evenly. **Table 3** shows experimental data sets. The number of individuals is set to 512 due to the capacity limit of our computer. The number of generations is set to 100 times because experiments have shown that the objective function value is usually not updated. In the experimental results of the previous study, if the delivery time interval was shorter than 25, crane interference occurred frequently, and manufacturing became impossible. For this reason, the delivery time interval is set to 25, which is the most severe. There are 10 experiments for each manufacturing pattern. The number of iterations in ILS is set to 300. In preliminary experiments, the time required for one generation change of GA was shown to be about three times the time required for one iteration of ILS. **Table 4** shows the manufacturing pattern. In actual manufacturing, it exists in countless numbers. Therefore, we classified the characteristics of actual operation and categorized the manufacturing pattern into 13 patterns. Its characteristics are "all jobs with the same work machines are continuous," "jobs with different work machines alternate," "jobs with a different number of work machines alternate or are continuous," etc.

### 6.2. Results of Computer Experiments

**Table 5** shows computer experiment results using an Intel core i3 level CPU. The objective function value (Best) and the objective function value (Average) are the best value and the average value of 10 experiments, respectively. The calculation time is the average value of 10 experiments. Lower limit is the sum of operation times for each machine and crane conveyance times for each crane without machine conflicts or crane interference.

The following were confirmed through computer experiments.

**Table 3.** Experimental data setting.

| Individuals | Generation | Products | Interval | Simulation | Iterations in ILS |
|---|---|---|---|---|---|
| 512 | 100 | 20 | 25 | 10 | 300 |

**Table 4.** Manufacturing pattern.

| Pattern | Production sequence | Characteristic |
|---|---|---|
| 1 | A→$B_1$→$B_2$→$B_4$→C | All the same machine |
| 2 | A→$B_1$→$B_2$ or $B_3$→$B_4$ or $B_5$→C | Machine of $B_2$ and $B_3$, $B_4$ and $B_5$ is unevenly processed |
| 3 | A→$B_1$→$B_3$→$B_4$→C<br>A→$B_1$→$B_2$→$B_5$→C | Machines of $B_2$ and $B_3$, $B_4$ and $B_5$ is alternatively processed |
| 4 | A→$B_1$→$B_4$→$B_5$→C<br>A→$B_2$→$B_4$→$B_5$→C<br>A→$B_3$→$B_4$→$B_5$→C | Operation allowance in the first half of the production |
| 5 | A→$B_1$ or $B_2$ or $B_3$→$B_4$→$B_5$→C | Machine of $B_1$, $B_2$ and $B_3$ is unevenly processed |
| 6 | A→$B_1$→$B_2$→$B_3$→$B_4$→C<br>A→$B_1$→$B_2$→C | The first half products are manufactuireded in 6 machines |
| 7 | A→$B_1$→$B_2$→$B_3$→$B_4$→C<br>A→$B_1$→$B_5$→C | The second half products are manufactuired in 4 machines |
| 8 | A→$B_1$→$B_2$→C<br>A→$B_1$→$B_2$→$B_3$→$B_4$→C | The first half products are manufactuired in 4 machines |
| 9 | A→$B_1$→$B_5$→C<br>A→$B_1$→$B_2$→$B_3$→$B_4$→C | The second half products are manufactuireded in 6 machines |
| 10 | A→$B_1$→$B_2$→$B_3$→$B_4$→C<br>A→$B_1$→$B_2$→C | The number of machine is 6→4→6→4→··· |
| 11 | A→$B_1$→$B_2$→$B_3$→$B_4$→C<br>A→$B_1$→$B_5$→C | |
| 12 | A→$B_1$→$B_2$→C<br>A→$B_1$→$B_2$→$B_3$→$B_4$→C | The number of machine is 4→6→4→4→··· |
| 13 | A→$B_1$→$B_5$→C<br>A→$B_1$→$B_2$→$B_3$→$B_4$→C | |

**Table 5.** Computer experiment results.

| Pattern | Objective function value (Best) GA | GA+DG | ILS | PR | Lower limit |
|---|---|---|---|---|---|
| 1 | 2710.2 | 2707.0 | 2716.0 | 2700.0 | 2700.0 |
| 2 | 2646.8 | 2645.8 | 2641.3 | 2952.0 | 2600.0 |
| 3 | 2666.0 | 2665.5 | 2665.5 | 3030.0 | 2600.0 |
| 4 | 2670.0 | 2670.3 | 2674.0 | 2993.5 | 2658.0 |
| 5 | 2678.0 | 2678.0 | 2678.5 | 3019.3 | 2658.0 |
| 6 | 2638.7 | 2638.7 | 2638.7 | 3001.5 | 2610.0 |
| 7 | 2625.0 | 2625.0 | 2625.0 | 3080.8 | 2600.0 |
| 8 | 3052.3 | 3051.8 | 3050.5 | 3388.5 | 2610.0 |
| 9 | 3278.3 | 3276.8 | 3253.5 | 3694.5 | 2600.0 |
| 10 | 2765.5 | 2766.0 | 2765.5 | 3172.8 | 2610.0 |
| 11 | 2645.3 | 2645.3 | 2645.3 | 3175.0 | 2600.0 |
| 12 | 2622.2 | 2622.2 | 2621.2 | 2869.3 | 2610.0 |
| 13 | 2600.0 | 2600.0 | 2600.0 | 2887.8 | 2600.0 |

| Pattern | Objective function value (Average) GA | GA+DG | ILS | PR |
|---|---|---|---|---|
| 1 | 2712.7 | 2708.9 | 2726.6 | 2702.0 |
| 2 | 2649.1 | 2649.0 | 2645.6 | 2987.3 |
| 3 | 2666.8 | 2666.3 | 2666.3 | 3099.6 |
| 4 | 2672.1 | 2671.4 | 2677.2 | 3010.1 |
| 5 | 2679.0 | 2680.4 | 2681.7 | 3020.5 |
| 6 | 2641.4 | 2642.5 | 2643.7 | 3007.5 |
| 7 | 2630.3 | 2631.2 | 2634.3 | 3093.0 |
| 8 | 3246.7 | 3228.2 | 3360.4 | 3393.4 |
| 9 | 3322.3 | 3324.2 | 3373.2 | 3706.2 |
| 10 | 2766.6 | 2767.2 | 2765.5 | 3207.3 |
| 11 | 2645.3 | 2645.3 | 2645.3 | 3206.7 |
| 12 | 2623.9 | 2624.5 | 2621.4 | 2892.4 |
| 13 | 2600.0 | 2600.0 | 2600.0 | 2972.8 |

| Pattern | Calculation time(second) GA | GA+DG | ILS | PR |
|---|---|---|---|---|
| 1 | 766.1 | 660.4 | 729.1 | 47.5 |
| 2 | 794.9 | 805.2 | 969.7 | 56.3 |
| 3 | 772.8 | 781.2 | 732.2 | 57.6 |
| 4 | 711.0 | 713.2 | 671.1 | 51.6 |
| 5 | 698.2 | 697.2 | 553.7 | 51.9 |
| 6 | 750.9 | 652.8 | 625.1 | 54.7 |
| 7 | 704.7 | 636.1 | 561.6 | 54.9 |
| 8 | 864.4 | 778.0 | 1021.6 | 56.5 |
| 9 | 792.5 | 713.9 | 834.3 | 57.4 |
| 10 | 766.3 | 684.6 | 1292.1 | 56.1 |
| 11 | 626.9 | 566.4 | 710.3 | 56.5 |
| 12 | 717.6 | 655.8 | 1123.9 | 54.6 |
| 13 | 585.2 | 530.6 | 719.2 | 56.0 |

(a) The method using metaheuristics (GA or GA+DG or ILS) improves the objective function value (Best) by 10% to 17% except pattern 1, as compared with the method using PR. These values exceed the lower limit by no more than 6%, except for patterns 8 and 9.

(b) The method using metaheuristics (GA or GA+DG or ILS) improves the objective function value (Average) by 5% to 17% except pattern 1, as compared with the method using PR. These values exceed the lower limit by no more than 6% except for patterns 8 and 9.

(c) The calculation time of the method using a metaheuristics (GA or GA+DG or ILS) is 10 to 23 times as long as that of the method using PR.

(d) The best objective function value (Best) among these three metaheuristics is obtained mostly from the method using ILS, and it is 10 patterns out of 13 patterns. On the other hand, there is no difference among the three metaheuristics for the best objective function value (Average). The objective function values of the method using GA and GA + DG are almost equal for both Best and Average.

(e) The calculation time of the method using ILS is shorter than that of the method using GA (GA, GA + DG) in Patterns 3 to 7. Other than the above, the calculation time of the method using GA is shorter than that of the solution method using ILS. The calculation time of the solution using GA + DG is shorter than that of the solution using GA, except for patterns 2 to 4.

When there are 20 products, the candidates of crane assignment are the 80th power of 2, which is a very large optimization problem. The method using PR can be solved in a short calculation time, within 60 seconds, but it cannot sufficiently search the above solution space. As a result of improving the above problem using the metaheuristics, the method using GA, GA + DG, or ILS can obtain a better solution. The calculation time is about 10 to 20 minutes, and it is considered that it can be applied to real problems. Among the three metaheuristics, the method using ILS often gives the best objective function value. However, it may take more calculation time than do the other two methods. It seems to be because it is searching more intensively around the good solution. The objective function values of the method using GA and GA + DG are almost equivalent. On the other hand, there are many cases where the calculation time of the method using GA + DG is short. The reason for this is considered to be that the calculation time of operation simulation is shortened because good solutions with little occurrence of crane interference are found in a few search iteration times from a variety of initial solutions of the method using GA + DG.

When designing a method using metaheuristics, it is important to balance the diversification and intensification of solution search [20]. In the future, we will introduce an index on the entropy of the solution and research an algorithm that balances intensive search around good solutions and searches without bias in the solution space.

## 7. Conclusion

We have proposed a scheduling algorithm using metaheuristics for production process with crane interference. As a result of comparing several metaheuristics, we confirmed that both searching for diverse solutions and intensively searching around the good solution are effective for finding suboptimal solutions. In the future, we plan to research a solution algorithm to realize intensification and diversification of search. More generally, we plan to develop algorithms for production processes with three or more cranes.

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