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A HEURISTIC SCHEDULING ALGORITHM FOR STEEL MAKING PROCESS WITH CRANE HANDLING

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Abstract There are a large number of multi-stage job-shop processes in production plants. Steel making process is also modeled as of a multi-stage job-shop process with crane handling. In the steel making process if there are two or more overhead traveling cranes for material handling in a house, it becomes very difficult to obtain in practice an optimal or near optimal solution under consideration of restrictions concerning crane interference caused between them as well as many restrictions for each facility in the house of production plant. In this paper, we first present a formulation of the scheduling problem taking account of the crane interference and then propose a heuristic algorithm to find a sub-optimal solution which starts at feasible solutions and solves the problem in a finite time. The algorithm is characterized by restricting search space and using hybrid method of depth-first search and width-first search on an enumeration tree for crane assignment. We also discuss an availability of this algorithm using a numerical simulation for a practical steel making process.

Keywords: Algoritm, logistics, manufacturing, scheduling, simulation

1. Introduction

In the Japanese industry, recent customer demands require high quality, quick delivery and large variety in products. In the situation the production scheduling has become more important in order to achieve an efficient operation, i.e. to minimize production cost and production lead-time. However in some plants it is difficult to find an optimal solution which satisfies all required constraints in a practical time, since the number of constraints of the production scheduling problem is so large as well as the number of variables. And also some more complex constraints will be set up because of more precise operations to obtain product quality required by customers. In the steel making process we observe the same situation and hence many production scheduling systems each of which finds a sub-optimal solution in a practical time have been developed for practical applications [1][2].

A scheduling problem which can be seen in the steel making process is characterized by material handling which is executed by one or more overhead traveling cranes (shortly refer it as "crane" hereafter). In some practical situations two or more cranes run on a same rail arranged just under a ceiling of a house. Consider such two cranes which are facilitated in a house. If one of them is going to convey a work from position A to position B and another to convey a work from position B to C simultaneously as shown in Figure 1, the two cranes will run against each other at some position between B and C. This is called as crane interference in this research. In order to avoid the crane interference we have to decide a priority or a schedule concerning the crane operation. The consideration of the crane interference makes a scheduling problem much more difficult since the problem has to be concerned with positions of cranes in the house as well as time horizon. This scheduling problem with the crane interference was found in a few researches [3][4].

In this paper, we first formulate the problem in section 2 and then propose a new heuristic algorithm in section 3 to find a sub-optimal solution in a practical finite time. In order to make the algorithm efficient it starts at feasible solutions and searches a better solution in a restricted search space. In the algorithm a hybrid method of depth-first search and width-first search is used on an enumeration tree for crane assignment. In section 4 we discuss validity and a practical availability of this algorithm using a numerical simulation for a steel making process.

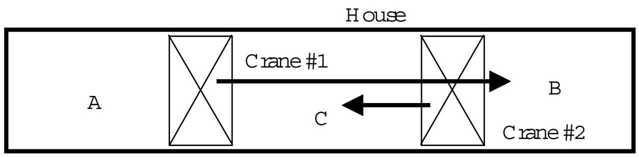

Figure 1: An illustrative example of crane interference

2. Process Description

2.1. Description of the model

We will consider a steel production system in which two or more cranes are facilitated to convey work-in-process (abbreviated by WIP hereafter) between processes. A typical example of the production system is depicted in Figure 2.

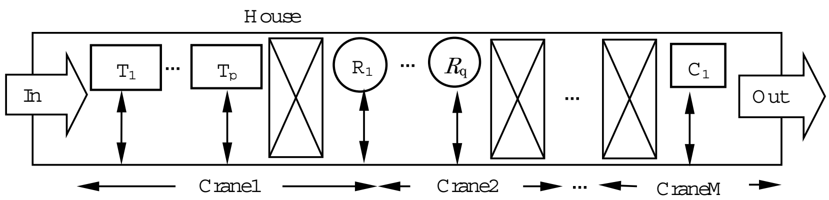

Figure 2: An example of steel making process with cranes

In the figure, materials are carried into the house in Figure 2 from the left side and carried out to the right side after completion of production. Each product requires three common processes which are denoted by T, R and C as shown in the figure. The first process T has more than one same facilities represented by T_1 to T_p. The second process consists of several facilities represented by R_1 to R_q, which are different from each other. Each product requires to be processed at one or more of them according to a predetermined order. The final process consists of a facility C_1 for every product. In this research we consider an extension of the plant depicted in Figure 2. A residing plant in practice has three houses, one of which corresponds to the layout depicted in Figure 2. Each of the other houses has a facility same as C_1 and also a few facilities similar to R.

2.1.1. Assumptions

In order to formulate the problem, the following assumptions are made. Assumptions (a) to (g) are concerning to facility, and (h) to (k) are made with respect to scheduling.

(a) The production sequence of products at the third process is given. Since this process is bottleneck one in practice, the schedule at the process must be made prior to the other processes. This priority is also required in order to obtain high quality products because the product quality is depend on the production sequence at the process.
(b) One product at each facility can be loaded at each time.
(c) Each product is not divided into two or more batches of the products.
(d) Two or more batches of the same quality product are not assembled into a batch of the product.
(e) A crane can handle a WIP at each time. When two or more cranes are facilitated in a house, interference caused by these cranes must be resolved. This means that the crane operation sequence is considered in the scheduling problem of this paper.
(f) No buffer stock of WIP is permitted. This restriction is made for sake of safety on operation in practice. Under the restriction if an operation at a facility completes for product J and if a facility used for the next operation of the product is occupied by other product, product J will stand by at the current facility until the facility for the next operation will become vacant.
(g) Each WIP is conveyed by a crane.
(h) Operating time at each facility is deterministic and known for each product.
(i) The sequence of facilities to be visited for each product is known excepting cranes.
(j) Each job has to arrive at the third process in a given time before completing the preceding job at the process, where a job corresponds to a task or WIP to produce a given product.
(k) Discrete planning horizon is used.

The objective of the problem is to minimize a sum of production lead-times of products, where the lead-time for each product is defined as the interval time until completing the product at process C after starting an operation at process T.

2.1.2. Crane interference and deadlock

The scheduling problem investigated in this research is characterized by the crane interference. It occurs when two or more cranes are facilitated in a house and when one or more of them move to interfering direction against the other as shown in Figure 3.

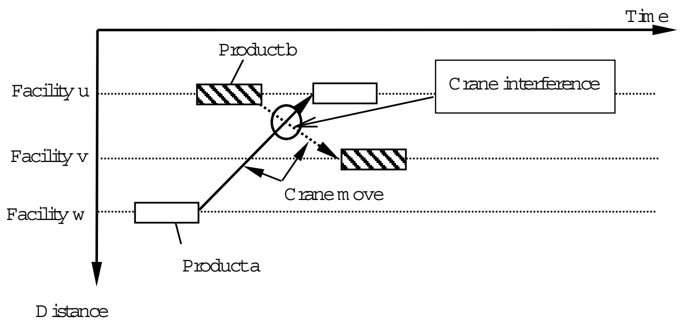

Figure 3: An example of crane interference

One more crucial problem is one called deadlock in practice. This problem becomes critical when only a crane handles WIPs. When a crane handles every WIP in a house, prior to conveying a WIP to a facility, the facility must be vacant, i.e. every job prior to the job for the WIP at the facility has to be completed. Even for a multiple crane case, a WIP has to be moved from a facility to the next facility after removing a WIP being operated at the next facility.

2.2. Notation

The following notations are used to formulate this problem.

t: Index to represent discrete time,
U: Set of products,
J_j: Job name required to produce product $j \in U$,
N_j: Set of operations required to produce product $j \in U$,
n_j: Number of operations for job J_j, i.e. $n_j = |N_j|$,
O_{ij}: The i^{th} operation for job J_j, $i = 1, \cdots, n_j$,
OM_{ij}: Set of facilities available to execute operation O_{ij},
OT_{ij}: Operating time to complete operation O_{ij},
ST_{ij}: Start time of operation O_{ij},
ET_{ij}: Completion time of operation O_{ij},
M: Number of cranes,
$CT(a, b)$: Moving time of crane from position a to position b in a house,
b_m: Position of facility m,
a_{ij}: Position of facility executing operation O_{ij} (i.e. $a_{ij} = b_m$, when facility m is assigned to O_{ij}),
d: Operation time of winding up or down a ladle by crane which is a known constant for every O_{ij},
δ: Minimum distance of two adjacent cranes for safety required in order to avoid their collision,
ν: Crane speed which is a known constant,
P_{kt}: Position of crane k at time t, $k = 1, \cdots, M$,
x_{ij}^m: 0-1 decision variable which is defined by,

$$x_{ij}^m = \begin{cases} 1: & \text{when facility } m \text{ is assigned to operation } O_{ij} \\ 0: & \text{otherwise} \end{cases}$$

$X_{i_1j_1,i_2j_2}^m$: 0-1 decision variable which is defined by,

$$X_{i_1j_1,i_2j_2}^m = \begin{cases} 1: & \text{when } O_{i_2j_2} \text{ is is operated after } O_{i_1j_1} \text{ at facility } m \\ 0: & \text{otherwise} \end{cases}$$

y_{ij}^k: 0-1 decision variable which is defined by,

$$y_{ij}^k = \begin{cases} 1: & \text{when crane } k \text{ is assigned to convey a WIP completed operation } O_{ij} \\ 0: & \text{otherwise} \end{cases}$$

Y_{ijt}^k: 0-1 decision variable which is defined by,

$$Y_{ijt}^k = \begin{cases} 1: & \text{when crane } k \text{ is occupied to convey a WIP completed operation } O_{ij} \text{ at time } t \\ 0: & \text{otherwise} \end{cases}$$

G: Sufficiently large constant value.

2.3. Formulation

The objective is to minimize the sum of production lead-times for all jobs. The problem is formulated as follows:

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

subject to

$$\sum_{m \in OM_{ij}} x_{ij}^m = 1 \quad \text{for each } O_{ij}, \quad (2)$$

$$\sum_{O_{ij}} X_{i_1 j_1, ij}^m = x_{i_1 j_1}^m \quad \text{for each } m \text{ and } O_{i_1 j_1}, \quad (3)$$

$$\sum_{O_{ij}} X_{ij, i_2 j_2}^m = x_{i_2 j_2}^m \quad \text{for each } m \text{ and } O_{i_2 j_2}, \quad (4)$$

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

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

$$ET_{ij} \geq ST_{ij} + OT_{ij} + 2d - 1 \quad \text{for each } O_{ij}, \quad (7)$$

$$ST_{i+1,j} \geq ET_{ij} + CT(a_{ij}, a_{i+1,j}) \quad \text{for each } O_{ij}, \quad (8)$$

$$\sum_k y_{ij}^k = 1 \quad \text{for each } O_{ij}, \quad (9)$$

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

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

$$a_{ij} = \sum_{m \in OM_{ij}} b_m x_{ij}^m \quad \text{for each } O_{ij}, \quad (12)$$

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

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

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

$$P_{k+1,t} \geq P_{k,t} + \delta \quad \text{for each } k \text{ and } t, \quad (16)$$

$$x_{ij}^m, \; y_{ij}^k \text{ and } Y_{ijt}^k \text{ are all 0-1 integer variables for every } m, k, t \text{ and } O_{ij}, \quad (17)$$

$$X_{i_1 j_1, i_2 j_2}^m \text{ is 0-1 integer variable for every } m, O_{i_1 j_1} \text{ and } O_{i_2 j_2}, \quad (18)$$

$$P_{kt} \geq 0 \quad \text{for every } k \text{ and } t. \quad (19)$$

Constraint (2) forces an appropriate facility to be assigned to each operation O_{ij}. Constraints (3) and (4) give a relationship between variables x_{ij}^m and $X_{i_1 j_1, i_2 j_2}^m$ where x_{ij}^m defines a facility assignment for each operation O_{ij} and $X_{i_1 j_1, i_2 j_2}^m$ defines a production sequence at the facility. Constraints (5) and (6) define a relationship between completion time of operation and beginning time of the successive operation processed at the same facility. Constraints (7) and (8) give completion time of operation O_{ij} and beginning time of the next operation of the same job, respectively.

Constraint (9) forces a crane to be assigned to a WIP which finishes operation O_{ij}. Constraint (10) shows that at most one product can be handled by a crane at a time.

Constraint (11) represents that if crane k is assigned to a WIP completed at a facility of operation O_{ij}, the crane is occupied by the WIP from time winding up a ladle in which the completed WIP is filled at the facility to time winding down the ladle at the next facility. The beginning time when the crane is occupied by the completed O_{ij} is equal to $ET_{ij} - d + 1$, and the completion time when the crane finishes winding down the WIP at the next facility is $ST_{i+1,j} + d - 1$. Constraint (12) shows that position of executing operation O_{ij} is equal to position of a facility assigned to O_{ij}. Constraints (13) and (14) give start position at time ET_{ij} and terminal position at time $ST_{i+1,j}$, respectively, for conveying a WIP completing operation O_{ij} (see Figure 4). Constraint (15) restricts crane movement in distance during one unit time. Constraint (16) forces every crane to keep a given distance δ at least from its adjacent crane (see Figure 4).

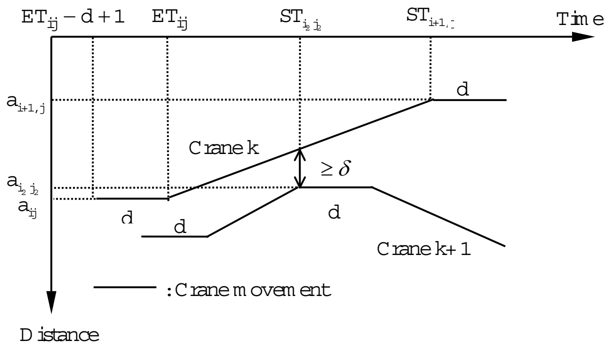

Figure 4: Relationship between two cranes

3. The Algorithm

3.1. Outline of the Algorithm

The scheduling problem formulated in the previous section is discussed in a context of multi-stage job-shop scheduling problem with cranes, and several algorithms are proposed [1]- [4]. If more than two cranes exist in a house , it is necessary to avoid crane interference in addition to many constraints of operation by each facility, and this scheduling problem becomes very complex. Imai et al. (1996 and 1997) propose an algorithm to satisfy various objectives and constraints by a combination of backward scheduling from a bottleneck process and forward scheduling using a discrete-simulation with rules of material handling by cranes, crane assignment rules and pick up timing rules. We propose an arrow diagram representation of each job and then develop heuristic algorithm using pert-calculation and two meta-heuristic algorithms[3]. Honda et al. (2002) propose an algorithm which uses a simulation to make a schedule satisfying a lot of constraints and which uses an enumeration tree to look for a feasible solution [4].

Forward simulation with heuristics so as to avoid crane interference is often applied in the past researches, but their algorithm based on forward simulation can't apply sometimes to the other scheduling problem. Meta-heuristic is applicable in a general situation, but it requires relatively longer computation time to re-schedule job and crane handling and to evaluate the improved solution.

In order to solve the problem formulated in section 2, we propose a new general algorithm which finds a sub-optimal solution by starting from feasible solutions. This algorithm consists of two-steps in which backward simulation and forward simulation are executed.

In the simulation processes a hybrid method which involves depth-first search and width-first search on an enumeration tree of crane assignment is applied so as to avoid crane interference. This algorithm is summarized as follows.

In the first step (**Step1** in the algorithm below), the latest due start time and latest due completion time for each operation are calculated using backward simulation by starting from the bottleneck process C. In this step, the facility scrambling is avoided, i.e. facility assignment to each operation is achieved, but the avoidance of crane interference isn't taken into consideration. In the second step (**Step2** to **Step4** in the algorithm), start time and completion time of each operation is calculated using forward simulation based on the latest due start time and the latest due completion time calculated in backward simulation. In this calculation process, a device to avoid crane interference and facility scrambling is installed.

Step1 The latest due operation start time for each job at each facility is calculated using backward simulation by starting from operation of bottleneck process C.

Step2 Create an enumeration tree of crane assignment in increasing order of the latest due operation start time, and decide crane assignment so as to minimize total lead-time between carrying-in-time into the house and carrying-out-time from the house for each job on the enumeration tree. Calculate the sum of lead-times for all jobs using forward simulation. Let D be a known constant which is a specified depth of the first search for crane assignment. If the depth of search on the enumeration tree is less than D, go to **Step3**. Otherwise go to **Step4**.

Step3 Enumerate all the candidates of the crane assignment from the first depth. For example, if the number of crane is M, enumerating of crane assignment is continued until the number of candidates becomes M^D. Make a schedule for each of all candidates in order to calculate lead-time between carrying-in-time and carrying-out-time using forward simulation. If the number of candidates is M^D, M^{D-1} candidates are selected according to the depth-first search. If all crane assignment is completed, the algorithm finishes. Otherwise return to **Step2**.

Step4 Enumerate M crane assignment for each of M^D candidates. Make a schedule for each of M^D candidates and then calculate lead-time between carrying-in-time and carrying-out-time using forward simulation. Then M^{D-1} candidates are selected in order to shorten lead-time according to width-first search. If assignment of all cranes is completed, the algorithm finishes. Otherwise return to **Step2**.

Using this algorithm, it is possible to find a sub-optimal solution from feasible solutions in a finite time according to searching range D set up in advance as a parameter.

3.2. Additional notation

The following notations are used to describe the algorithm in addition to notations presented in §2.2.

T**:** The set of operations scrambling the same facility,

V**:** The set of crane conveyance arranged in increasing order of the latest due start time calculated in backward simulation,

Q**:** The set of operation whose completion time is delayed,

q**:** Index of crane conveyance in set V,

p**:** The situation of crane carriage operation assignments to crane facility from crane carriage operation 1 to q ($1 \leq p \leq M^D$),

W_q^p**:** A schedule of cranes for situation p,
EW_q^p**:** Evaluation value of W_q^p,
D**:** Specified depth parameter used in the depth first search for crane assignments,
ds**:** Depth index in the depth first search,
s_{ij}**:** Crane departure time at a facility completing operation O_{ij},
e_{ij}**:** Crane arrival time at a facility processing the next operation of O_{ij},
s^*_{ij}**:** Crane departure time at a facility completing operation O_{ij} when crane interference is avoided for the operation,
e^*_{ij}**:** Crane arrival time at the next operation of O_{ij} when crane interference is avoided,
a^*_{ij}**:** Start position of crane to convey a WIP completed operation O_{ij} when crane interference is avoided,
w_{ij}**:** Waiting time at the facility until start of conveyance after completing operation O_{ij},
BST_j**:** Start time of job J_j at the 3rd process C_1,
RST^k_{ij}**:** Operation start time of O_{ij} which is re-calculated for crane assignment k so as to avoid crane interference,
RET^k_{ij}**:** Operation completion time of O_{ij} which is re-calculated for crane assignment k so as to avoid crane interference.

3.3. The backward simulation

In this backward simulation, the latest due start time and the latest due completion time for each operation is computed by starting from the bottleneck process. In this step, only the facility scrambling is avoided, but the avoidance of crane interference isn't taken into consideration. The algorithm of backward simulation is as follows:

Step1 Set U, J_j and O_{ij}.
Step2 Calculate the latest due start time and the latest due completion time for each operation of J_j in decreasing order of the start time at the bottleneck process, i.e. BST_j in (7) and (8), using backward simulation. Set $T \leftarrow T + \{O_{ij}\}$, if operation time of O_{ij} is shifted to avoid a facility scrambling for the operation.
Step3 Set $U \leftarrow U - \{J_j\}$. If $U \neq \phi$, return to **Step2**. Otherwise go to **Step4**.
Step4 If $T \neq \phi$, improve the solution by simple local search [5][6]. Otherwise stop.

3.4. The forward simulation

In this forward simulation, start time and completion time for each operation is determined by executing the forward simulation based on the due start time and the due completion time obtained in the backward simulation, where crane interference and facility scrambling are tried to avoid in this step.

The method to avoid interference between two adjacent cranes, say crane k and crane $k+1$, is mentioned first and then the description of the algorithm is given. We put premises for simplicity without loss of generality as follows.

(a) Crane k is located at a left position of crane $k+1$.
(b) Crane k is assigned to convey a WIP completed operation O_{ij} , say conveyance k, and crane $k+1$ to convey a WIP completed operation O_{mn}.
(c) After completion of conveyance k, start time and completion time of conveyance $k+1$ is computed so as not to interfere with conveyance k.

(d) Any crane interference doesn't occur before the start time of conveyance $k+1$.

There are two methods for a crane to avoid crane interference with respect to the position and movement of two adjacent cranes. For crane $k+1$ one is to stop at its present position and another is to move to a safe direction.

(a)Crane $k+1$ stops at its present position and shifts start time(see Figure 5)

Crane $k+1$ can avoid interference at position a_{mn} shown in Figure 5 when (20) is satisfied for notation given in Figure 5, i.e. it will continue stopping till time s^*_{mn} given by (21) so as to avoid interference.

$$a_{mn} \geq a_{i+1,j} + \delta. \tag{20}$$
$$s^*_{mn} = e_{i+1,j} + d - (a_{mn} - (a_{i+1,j} + \delta))/\nu. \tag{21}$$

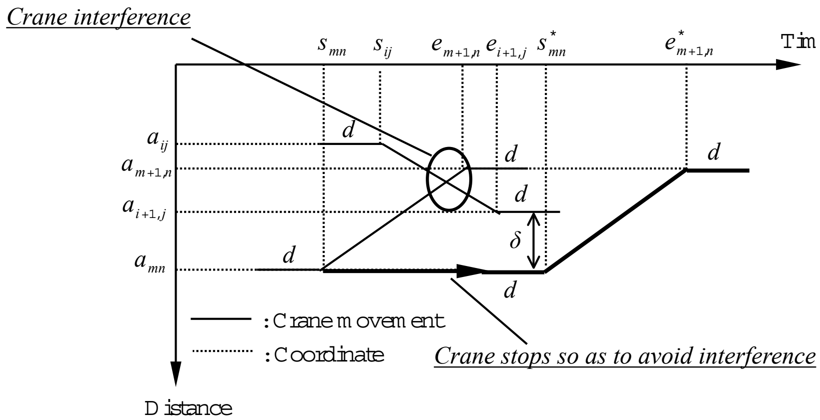

Figure 5: Crane stops so as to avoid interference

(b)Crane $k+1$ moves and shifts start time (see Figure 6)

Crane $k+1$ can't avoid interference by stopping at position a_{mn} when (22) is satisfied, where notation is defined in Figure 6. In this case crane $k+1$ will move to position a^*_{mn} given by (23) and then returns to a_{mn}. Crane $k+1$ will start its task at time s^*_{mn} given by (24).

$$a_{mn} \leq a_{i+1,j} + \delta. \tag{22}$$
$$a^*_{mn} = a_{i+1,j} + \delta. \tag{23}$$
$$s^*_{mn} = e_{i+1,j} + d + (a^*_{mn} - a_{mn})/\nu + d. \tag{24}$$

The algorithm of forward simulation is as follows.

Step1 Set D, W_0^1 and V, where W_0^1 is an initial solution of backward simulation. Set $ds = 0$ and $q = 1$.

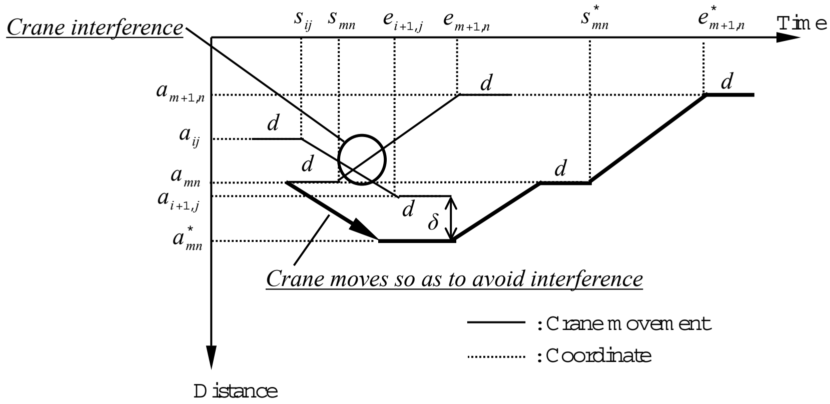

Figure 6: Crane moves so as to avoid interference

Step2 Pick up the earliest crane conveyance q from V. Set $W_q^p \leftarrow W_{q-1}^r$ and $EW_q^p \leftarrow EW_{q-1}^r$. The value of index p is $(h-1)M+1$ to hM, where $1 \leq h \leq r$. The relationship among r, p and ds is given by (25) and (26).

$$r = \begin{cases} M^{ds} & (0 \leq ds \leq D-1) \\ M^{D-1} & (ds \geq D). \end{cases} \tag{25}$$

$$p = (h-1)M+1, (h-1)M+2, \cdots, hM \quad (1 \leq h \leq r). \tag{26}$$

Step3 Assign q to crane k $(1 \leq k \leq M)$ under situation p and calculate $RST_{i+1,j}^k$ using (27). Avoid crane interference by the following **Step3.1** to **Step3.2**.

$$RST_{i+1,j}^k = ET_{ij} + CT(a_{ij}, a_{i+1,j}) - 1 + w_{i,j}. \tag{27}$$

Step3.1 Check interference of crane $k+1$ to the adjacent crane from start time to completion time of conveyance by crane $k+1$.

Step3.2 If crane $k+1$ doesn't interfere, go to **Step4**. Otherwise avoid any interference applying (20) $\sim$ (24) and return to **Step3.1**.

Step4 If $RST_{i+1,j}^k \neq ST_{i+1,j}$ adjust the start time and completion time of operations for each job which starts after present time by the following **Step4.1** to **Step4.5**. Otherwise go to **Step5**.

Step4.1 If $RST_{i+1,j}^k < ST_{i+1,j}$, change completion time of $O_{i+1,j}$ by (28). Go to **Step5**.

$$RET_{i+1,j} = RST_{i+1,j}^k + OT_{i+1,j} + 2d - 1. \tag{28}$$

Step4.2 If $RST_{i+1,j}^k > ST_{i+1,j}$, initialize Q. Set $Q \leftarrow Q + \{O_{i+1,j}\}$.

Step4.3 Arrange Q in increasing order of the completion time. If the first element of Q, say O_{mn}, has the next operation, calculate $RST_{m+1,n}^k$ using (29) and $RET_{m+1,n}^k$ using (30) for $O_{m+1,n}$, and set $Q \leftarrow Q + \{O_{m+1,n}\}$. Otherwise go to **Step4.5**.

$$RST_{m+1,n}^k = RET_{mn}^k + CT(a_{mn}, a_{m+1,n}) - 1 + w_{mn}. \tag{29}$$

$$RET_{m+1,n}^k = RST_{m+1,n}^k + OT_{m+1,n} + 2d - 1. \tag{30}$$

Step4.4 If $RET^k_{m+1,n} > ET_{m+1,n}$, set $Q \leftarrow Q + \{O_{m+1,n}\}$. If $O_{m+1,n}$ and the next operation, say O_{uv}, at the facility which is scrambled by operation $O_{m+1,n}$. Avoid this scramble by (31) and (32). Set $Q \leftarrow Q + \{O_{uv}\}$.

$$RST^k_{uv} = RET^k_{m+1,n}. \quad (31)$$

$$RET^k_{uv} = RST^k_{uv} + OT_{uv} + 2d - 1. \quad (32)$$

Step4.5 Set $Q \leftarrow Q - \{O_{mn}\}$. If $Q = \phi$ go to **Step5**. Otherwise return to bf Step4.3.

Step5 Set schedule W^p_q and calculate EW^p_q using (33) based on results of **Step2** to **Step4** for each p.

$$EW^p_q = \sum_{Q_{ij} \in J_j} (RET^k_{ij} - ET_{ij}). \quad (33)$$

Step6 Set $V \leftarrow V - \{O_{ij}\}$ and set $ds \leftarrow ds + 1$. If $ds < D$, set $q \leftarrow q + 1$, $ST_{ij} \leftarrow RST^k_{ij}$ and $ET_{ij} \leftarrow RET^k_{ij}$, for each k, i and j, return to **Step2**. Otherwise go to **Step7**.

Step7 In increasing order of EW^p_q, M^{D-1} candidates of crane assignment are selected.

Step8 If $V = \phi$, stop the algorithm and print out solution W^p_q whose EW^p_q is smallest. Otherwise, set $q \leftarrow q + 1$ and return to **Step2**.

4. Numerical example

We apply the algorithm developed in this research to a practical scheduling problem in a steel making process using one-day production data. The steel making process used in the numerical example consists of five processes except crane handling. Third process is the bottleneck process. We apply the algorithm developed in this research for the first three processes, and apply the forward simulation to the last three processes. The steel making process has three houses. The number of cranes in the first house, the second house and the third house are two, two and one, respectively.

Ladle cars carry products between houses. Only one product is carried by one ladle car at a time. Therefore we handle ladle cars as the facilities for operations in our algorithm.

An example data used in our simulation is extracted as shown in Table 1. Note that the simulation data is scaled data. Three same facilities are located as the first process, say facility 11 to 13. At the first process, assignment of WIPs to the facilities has to be decided in the solution process. Therefore representative facility (facility 10) is assigned first as an initial facility as shown in Table1. There are six facilities in the second process (facility 21 to 26), two facilities in the third process (facility 31 to 32), three facilities in the fourth process (facility 41 to 43), two facilities in the fifth process (facility 51 to 52) and four ladle cars (facility L1 and facility L4). Facility name and operation time at the facility are illustrated for each Job given by number in Table 1. For example, operation time of facility 10 is 9.00 for Job 1001. Crane handling operation is required between adjacent facilities in Table 1, e.g. between facility 10 and facility 24 for Job 1001. It is required to complete 30 to 40 jobs one-day. The number of facilities to be required to complete each job is 6 to 9 excepting crane handling operations. Therefore the total number of facilities required to complete a job including crane handling operation becomes up to 11 to 17.

Table 1: Example of computer simulation data

Job No	Facility	Time	Facility	Time	Facility	Time	Facility	Time	Facility	Time	Facility	Time	Facility	Time
1001	10	9.00	24	0.60	31	6.78	41	0.60	L1	0.40	51	6.00	-	-
1002	10	9.00	24	0.60	31	6.34	41	0.60	L1	0.40	51	6.00	-	-
1003	10	9.00	24	0.60	31	7.06	41	0.60	L1	0.40	51	6.00	-	-
1004	10	9.00	24	0.60	31	7.06	41	0.60	L1	0.40	51	6.00	-	-
1005	10	9.00	24	0.60	31	7.06	41	0.60	L1	0.40	51	6.00	-	-
1006	10	9.00	21	1.00	12	6.00	31	7.34	41	0.60	L1	0.40	52	6.00
1007	10	9.00	21	1.00	12	6.00	31	8.44	41	0.60	L1	0.40	52	6.00
1008	10	9.00	21	1.00	12	6.00	31	8.44	41	0.60	L1	0.40	52	6.00
1009	10	9.00	21	1.00	12	6.00	31	8.44	41	0.60	L1	0.40	52	6.00
1010	10	9.00	21	1.00	12	6.00	31	8.44	41	0.60	L1	0.40	52	6.00
1011	10	9.00	21	1.00	12	6.00	31	8.44	41	0.60	L1	0.40	52	6.00
1012	10	9.00	21	1.00	12	6.00	31	8.44	41	0.60	L1	0.40	52	6.00
...	...	...	...	...	...	...	...	...	...	...	...	...	...	...

Evaluation value is ratio of total lead-time obtained by forward simulation to one by backward simulation as shown in (34).

$$Evaluation\ value \quad = \quad \sum_{J_j \in U} (RET^*_{N_j,j} - RST^*_{1j}) / \sum_{J_j \in U} (ET_{N_j,j} - ST_{1j}), \qquad (34)$$

where RET^*_{ij} and RST^*_{ij} are results obtained by the forward simulation.

Some of simulation results are shown in Figure 7 and Table 2, where notation D represents a specified depth from the first crane assignment. CPU of our computer utilized in the simulation is Intel Celeron with 1.5GHz clock frequency, and main memory size 512Mb. Although three facilities are installed at the first process, it is enforced that one of them pauses through a simulation run. Therefore there are three cases in simulation runs. Facility to pause at the first process is set up in the parameter. If the value of D increases, the evaluation value improves as shown in Figure 7, and it converges to one when D takes value more than 4. Computation time (elaps time) to obtain a schedule by our algorithm corresponding to Figure 7 is shown in Table 3. The computation time takes less than 80 seconds, when the depth is set to 8.

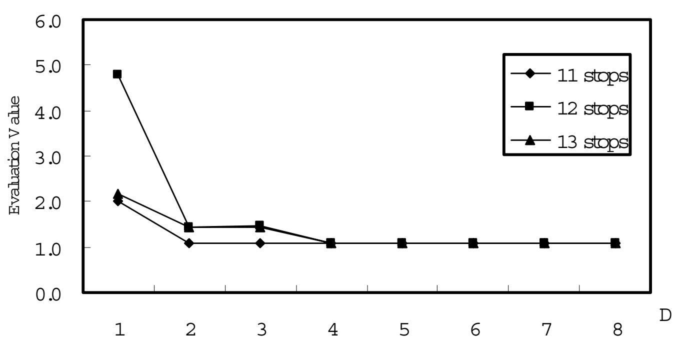

Figure 7: Example of computer simulation results

In order to discuss a validity of our algorithm developed in this research, 1000 schedules are made by assigning crane using uniform random numbers. Distribution of evaluation values obtained by the 1000 schedules is depicted in Figure 8, where facility 11 at the first process is paused. From Figure 7, Table 2 and Figure 8, the results show that a validity of the algorithm is confirmed and also must be relatively superior.

Table 2: Example of computer simulation results

D	Facility to stop		
	11	12	13
1	2.007750	4.797185	2.172451
2	1.079333	1.422356	1.437986
3	1.079333	1.476113	1.437986
4	1.077882	1.086296	1.071508
5	1.077882	1.086296	1.071508
6	1.077882	1.086296	1.071508
7	1.077882	1.086296	1.071508
8	1.078124	1.086652	1.070602

Table 3: Computation time of computer simulation in Figure 7

D	Facility to stop		
	11	12	13
1	1.2	1.8	1.8
2	2.4	2.4	2.4
3	3.0	3.6	3.6
4	6.0	6.0	6.0
5	10.8	10.8	10.2
6	20.4	20.4	19.8
7	39.0	39.0	38.4
8	78.0	77.4	76.2

In the actual production planning whose data is used in the example, operation start time at facility for each job is determined by subtracting total operation time taken between the facility and a bottleneck process (= third process in this case) from operation start time at the bottleneck process. Since the operation time involves some allowance, the evaluation values in the actual production planning becomes 1.1 to 1.2 which are greater than values shown in Table 2. This means that the schedule obtained using our algorithm is better than one obtained in the actual production planning.

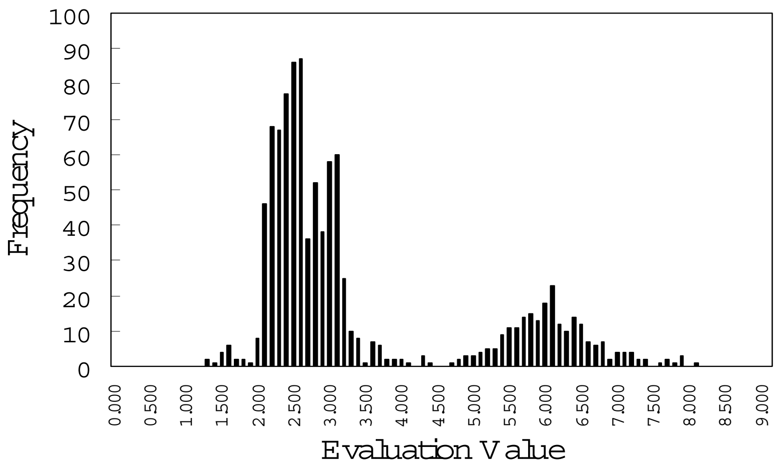

Figure 8: Histogram of evaluation value by random crane assignment

5. Conclusion

In this paper, we propose an algorithm to find a sub-optimal schedule for steel making process in which materials are handled by overhead traveling cranes. The algorithm restricts solution search range and utilizes a hybrid method of depth-first search and width-first search on an enumeration tree of crane assignment. The algorithm can find a sub-optimal solution in a finite time. We also realize availability of this algorithm to use at an actual steel making process by combining a numerical simulation. This algorithm is thought to be available for real-time scheduling, because it finds a sub-optimal solution in which crane movement is taken into consideration as well as finding it in a short time.

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