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The coordinated scheduling of steelmaking with multi-refining and tandem transportation

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Abstract: This article explores coordinated scheduling problem arising in steelmaking and multi-refining operations. Jobs are first processed in converters and then transported downstream to be processed in refining furnaces in which two different transporters are employed in tandem at the stage of transportation. There exist multi-refining jobs. The objective is to minimize the maximum completion time satisfying no transporters conflict and buffer space. For the model, we develop a tabu search algorithm and provide the worst case analysis. Computational tests are evaluated to show the efficiency brought by the tabu search algorithm relative to lower bound and sequenced and separately algorithm.

1. INTRODUCTION

This problem is motivated by the coordinated scheduling of steelmaking-refining of a steel plant. An important stage before the production of CCM is steelmaking-refining operation, in which jobs from converters are transported to refining furnaces where different special elements are added. The filling of one converter is defined as a 'job' in this scheduling. The purpose of refining operation is to subject the jobs to element requirement for subsequent operation. Usually, there are three types of refining called LF, RH, CAS and exist more than one machines for each type of refining settled in different refining spans (working areas where refining furnaces settled in). As shown in figure 1. Those jobs to be processed only in refining LF are called LF jobs, and similarly jobs to be processed only in refining RH (CAS) are called RH (CAS) jobs. Those jobs to first be processed in refining LF (RH) and then in RH (LF) are called LF+RH (RH+LF) jobs. Jobs to be processed in refining LF, RH, CAS consequently are called LF+RH+CAS jobs.

Note that the tracks and the rails where cranes travelling on are vertical since the tracks and refining spans are vertical. There is exactly one trolley travelling on each track and may exist one or two cranes travelling on one refining rail. Each capacity of a trolley or a crane is one. Jobs to be processed in the same converter share one trolley and jobs to be processed in those refining furnaces settled in the same span share one or two cranes.

There are no buffer spaces between steelmaking and refining. If the trolley was not available when the job has been finished, the starting time of current job in converter must be delayed. If no crane is available when the trolley has finished the transportation, the job being transported must wait with occupying the trolley. If the proceeding job is not finished when the current job has arrived refining furnace, the current job must wait without occupying the crane.

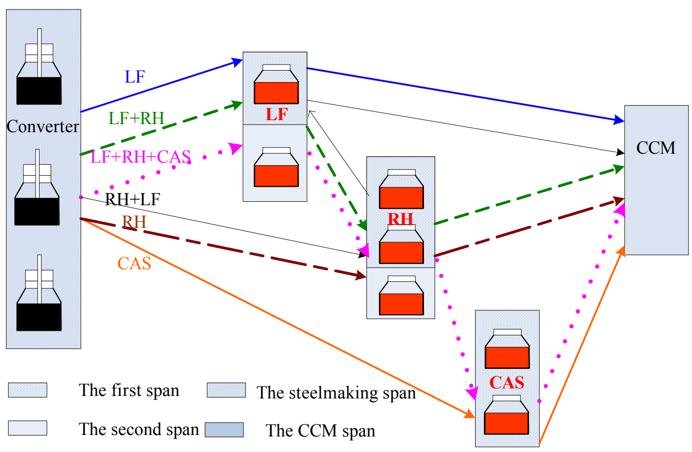

Fig 1 Flow of multi-refining jobs from converters to refining furnaces

Coordinated scheduling problem with transportation consideration has been one of the most important topics in the last ten years. *Lee and Chen* (2001), and *Chang and Lee* (2004) study semi-finished jobs and finished jobs delivery in flowshop and parallel environments. *Wang and Cheng* (2000) consider the scheduling problem with two different transportation modes is available. For crane scheduling problem, only few different alternative approaches have been proposed in reactive. *Lim et. al.* (2007) study the m-parallel crane scheduling problem with non-crossing problem motivated by crane scheduling in ports. *David et. al.* (2006) focus on the case where multiple cranes, sharing the same rail, are used to convey a single type of jobs along the line according to a given production sequence. *Takashi et. al.* (2006) consider steelmaking scheduling problem with cranes while not consider multi-refining. There are seldom papers consider transporters coordinated problem in a steel plant especially with multi-refining consideration. *Tang et.al.* (2000) study the steelmaking-continuous cast problem without refining and transportation consideration.

2. PROBLEM DESCRIPTION

Our problem can be formally stated as follows. Jobs of set $N = \{J_1, J_2, \ldots, J_n\}$ to first be processed on parallel machines (converters) settled in steelmaking span and then transported to one or more refining furnaces downstream according to requirement. The transportation system composed of trolleys and cranes. Transportation between steelmaking and refining is first executed by trolleys travelling on the tracks behind converters and then by cranes travelling on the rail above refining spans. Transportation between refining furnaces in the same span is executed by cranes.

Job-independent transportation times from converters to refining furnaces and transportation times between refining furnaces are explicitly considered. Additionally, non-crossing constraint for two cranes in the same refining span is considered too.

The scheduling decision is to find both feasible processing machines and transporters, and furthermore, feasible starting times in processing machines and transporters for all jobs. The objective is to minimize the maximum completion time satisfying no transporters confliction and buffer limitation.

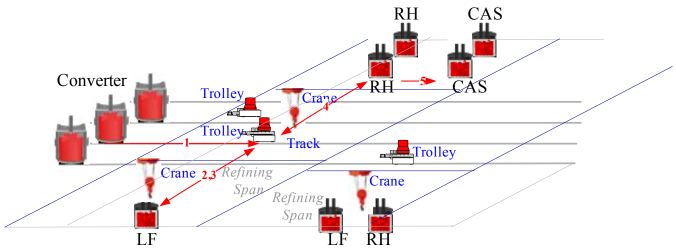

Fig 2 Figure for plan of one 3-refining job from converter to refining furnaces in a steel plant

As in the practice of a steel plant, there are 3 converters settled in steelmaking span, 2 RH, 1 LF and 2 CAS refining furnaces settled in refining span 1 sharing two cranes, and 1 RH and 1 LF refining furnace settled in refining span 2 sharing one cranes. Jobs to be processed contain LF, RH, CAS, LF+RH, RH+LF, and LF+RH+CAS jobs. It is obvious that the problem is more complex than three machines parallel problem, thus, is a strongly NP hard problem. Consequently, it is impossible to find a polynomial or pseudo-polynomial algorithm to solve it optimally unless P = NP. Job processing times in converters are about 30 minutes and in refining furnaces are about 15 minutes respectively. The transportation time between different types of refining may be 1 or 5 minutes.

Now, we provide parameters, variables and the mathematical model for the practical problem of a steel plant:

Φ The set of all steelmaking furnaces, $|\Phi| = C$, where C is the total number of steelmaking furnaces.

Ω The set of jobs, $\Omega = \{1, 2, \ldots, N\}$, where N is the total number of jobs.

Ψ The set of all refining furnaces, $|\Psi| = Q$, where Q is the total number of refining furnaces.

$\{qr\}$ The set of all jobs to be processed in the *rth* refining of type q only, where N_{qr} is the number of jobs, $q \in \{LF, RH, CAS\}$, $r \in \{1, 2, 3\}$, $\{q\} = \{q1\} \cup \{q2\} \cup \{q3\}$.

$\{qr+q'r'\}$ The set of all jobs to first be processed in the *rth* refining of type q and then in the r'*th* refining of type q', where $N_{qr+q'r'}$ is the number of jobs, $q, q' \in \{LF, RH\}$, $r, r' \in \{1, 2, 3\}$, $\{q+q'\} = \bigcup_{r,r'} \{qr+q'r'\}$.

$\{LF+RH+CAS\}$ The set of all jobs to first be processed in LF refining and then in RH refining, finally in CAS refining, where $N_{LF+RH+CAS}$ is the number of jobs.

Hh_j The index of span in which the crane transporting job j settled in, where h_j is the crane transporting of j.

t Transportation time of trolley from converter to crane which is the same as the transportation time of crane from trolley to refining furnace. Thus, the transportation time from one converter to refining furnace and from one refining furnace to another refining furnace settled in opposite direction in the same span are both $2t$.

t' Transportation time of crane from one refining furnace to another adjacent refining furnace.

P^i_j Processing time of job j in the $(i+1)th$ processing machine it passed through, $i = 0, 1, 2, 3$.

S^i_j Production starting time of job j in the $(i+1)th$ processing machine it passed through, $i = 0, 1, 2, 3$.

C^i_j Completion time of job j in the $(i+1)th$ processing machine it passed through, $i = 0, 1, 2, 3$.

s^i_j Transportation starting time of the crane which transport job j to the $(i+1)th$ refining it passed through, $i = 0, 1, 2$.

e^i_j Transportation completion time of the crane which transport job j to the $(i+1)th$ refining it passed through, $i = 0, 1, 2$.

$x_{jck} = \begin{cases} 1 \\ 0 \end{cases}$ If job j is processed in the kth position of the cth converter. Else if.

$y_{jqrl} = \begin{cases} 1 \\ 0 \end{cases}$ If job j is processed in the lth position of the rth refining of type q. Else if.

$z_{jcqr} = \begin{cases} 1 \\ 0 \end{cases}$ If job j is processed in the cth converters, and the first refining it passed through is the rth refining of type q. Else if.

$r_{jqrq'r'} = \begin{cases} 1 \\ 0 \end{cases}$ If job j is processed in the rth refining of type q and the immediately later refining furnaces it passed through is $r'th$ refining of type q'. Else if.

Objective function

Minimize $\left\{ \max_{0 \le j \le N} \left\{ C^1_j, C^2_j, C^3_j \right\} \right\}$

Constrains between S^i_j and C^i_j

$$C^i_j = S^i_j + P^i_j \qquad j = 1, 2, \ldots, N, i = 0, 1, 2, 3 \quad (1)$$

$$C^0_j + 2t \le S^1_j \qquad j = 1, 2, \ldots, N \quad (2)$$

$$C^1_j + 2t \le S^2_j \qquad j \in \{LF + RH, LF + RH + CAS\}, Hh_j = 1, h_j = 1 \quad (3)$$

$$C^1_j + t' \le S^2_j \qquad j \in \{LF + RH, RH + LF\}, Hh_j = 2 \quad (4)$$

$$C^2_j + t' \le S^3_j \qquad j \in \{LF + RH + CAS\}, Hh_j = 1, h_j = 2, \quad (5)$$

Completion time constraints of two adjacent jobs in converters

$$\sum_{j=1}^{N} S^0_j x_{jck} \ge \sum_{i=1}^{N} C^0_i x_{ick-1} \qquad c = 1, \ldots, C, k = 2, \ldots, N \quad (6)$$

$$\sum_{j=1}^{N} C^0_j x_{jck} \ge \sum_{i=1}^{N} C^0_i x_{ic,k-1} + 2t \qquad c = 1, \ldots, C, k = 2, \ldots, N \quad (7)$$

Starting time constraints of two adjacent jobs in refining furnaces

$$\sum_{j=1}^{N} S^i_j y_{jqrl} \ge \sum_{q'=1}^{Q} \sum_{r'=1}^{q_r} \sum_{h=1}^{N} C^1_h y_{hqr,l-1} r_{hqrq'r'} + \sum_{i=2}^{3} \sum_{q'=1}^{Q} \sum_{r'=1}^{q_r} \sum_{h=1}^{N} C^i_h y_{hqr,l-1} r_{hq'r'qr}$$

$$q = 1, \ldots, Q, r = 1, \ldots, q_r, l = 1, 2, \ldots, N, i = 1, 2, 3 \quad (8)$$

Non-crossing constraints of cranes

$$(s^v_j - s^1_i)(e^v_j - s^1_i) \ge 0$$

$$h_i = h_j \text{ or } i \in \{LF + RH, LF + RH + CAS\}, j \in \{RH, CAS, LF + RH + CAS\}, h_i \ne h_j, Hh_i = Hh_j, v = 0,2. \quad (9)$$

$$(s^1_i - s^v_j)(e^1_i - s^v_j) \ge 0$$

$$h_i = h_j \text{ or } i \in \{LF + RH, LF + RH + CAS\}, j \in \{RH, CAS, LF + RH + CAS\}, h_i \ne h_j, Hh_i = Hh_j, v = 0,2. \quad (10)$$

Unique position constraints of jobs(omitted)

3. PROPERTIES AND DOMINANCE RULES

In this section, we present two properties of the problem formulated in the previous section. Both of them describe the relationship between transportation starting time and finishing time of two non-crossing jobs to be processed in the same refining span.

Property 1: In an optimal scheduling, two jobs transported by one cranes must satisfy $(s^{v1}_j - s^{v2}_i)(e^{v1}_j - s^{v2}_i) \ge 0$ and $(s^{v2}_i - s^{v1}_j)(e^{v2}_i - s^{v1}_j) \ge 0$, where $v1, v2 \in \{0,1,2\}$.

Proof: There are two feasible scenarios for two jobs transported by one crane, *i.e.*, if $s^{v2}_i > s^{v1}_j$, then $s^{v2}_i > e^{v1}_j$; if $s^{v2}_i < s^{v1}_j$, then $e^{v2}_i \le s^{v1}_j$. The former (later) implies that job i (j) can start the transportation only when the transportation of job j (i) has been completed.

Property 2: In an optimal scheduling, two jobs transported by two cranes settled in the same rail must satisfy $(s^{v1}_j - s^{v2}_i)(e^{v1}_j - s^{v2}_i)(s^{v1}_j - e^{v2}_i)(e^{v1}_j - e^{v2}_i) \ge 0$, where $v1, v2 \in \{0,1,2\}$.

Proof: There are four feasible scenarios for the given cranes schedule: $s^{v1}_j > s^{v2}_i$, $e^{v1}_j > s^{v2}_i$, $s^{v1}_j > e^{v2}_i$, $e^{v1}_j > e^{v2}_i$, this implies that job j starts the transportation only when the transportation of job i has been completed; $s^{v1}_j > s^{v2}_i$, $e^{v1}_j > s^{v2}_i$, $s^{v1}_j < e^{v2}_i$, $e^{v1}_j < e^{v2}_i$, this implies that the transportation starting time of job i earlier than that of job j and transportation completion time of job *i* later than that of job *j*; $s^{v1}_j < s^{v2}_i$, $e^{v1}_j > s^{v2}_i$, $s^{v1}_j < e^{v2}_i$, $e^{v1}_j > e^{v2}_i$, this implies that the transportation starting time of job *j* earlier than that of job *i* and transportation completion time of job *j* later than that of job *i*; $s^{v1}_j < s^{v2}_i$, $e^{v1}_j < s^{v2}_i$, $s^{v1}_j < e^{v2}_i$, $e^{v1}_j < e^{v2}_i$, this implies that job *i* starts the transportation only when the transportation of job *j* has been completed.

We then provide two dominance rules to show the priority of different type of jobs in one refining furnace.

Dominance rule 1: In an optimal schedule, jobs of set {*LF+RH+CAS*} take precedence of jobs of set {*LF+RH*} ({*LF*}) in refining *RH* (*LF*) if transporter after processing is available.

Proof: We note that the processing times in three types of refining furnace are similar for all jobs. If transporter is available, we can always get smaller makespan by processing jobs of set {*LF+RH+CAS*} earlier since it may reduce the idle time in mult-refining furnace, thus reduce the makespan.

Dominance rule 2: In an optimal schedule, jobs of set {*LF+RH*} (or {*RH+LF*}) take precedence of jobs of set {*LF*} (or {*RH*}) in one *LF* (*RH*) refining furnace if transporter after refining is available.

Proof is omitted.

4. TABU SEARCH ALGORITHM

Now we are ready to present our tabu search algorithm which can provide an upper bound of optimal function value.

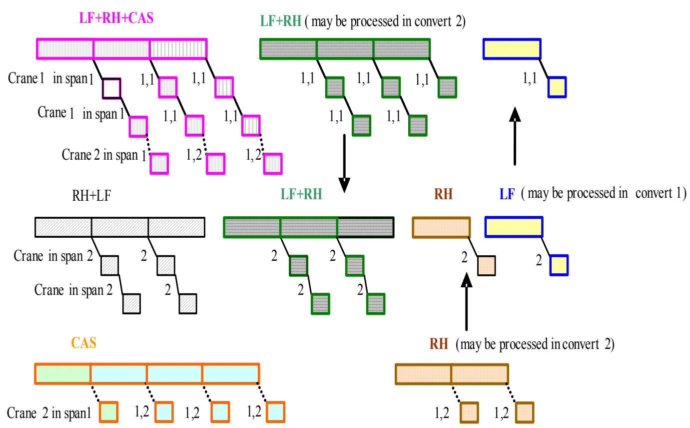

Fig 3 Gantt chart of permutation π^0

Tabu search, introduced by *Glover* (1989), is a universal procedure to gain good solution for combinatorial optimization problem. In this section, we provide a tabu search algorithm for this coordinated problem which contains only fundamental elements called move, neighborhood, initial solution, searching strategy, memory, aspiration criterion, stopping rule. Short-term memory (Z^*, T^*) stores in Z^* the best unperformed move associated with the currently best permutation π^{TS} and in T^* the tabu list associated with π^{TS}. The aspiration criterion is denoted as the current optimal function value. The stopping criterion is defined as the starting processing time of the last job in any converter no larger than the completion time of those last jobs processed in other converters or the total recurrence times larger than n(n+1)/2. The working of our tabu search algorithm can be explained as follows:

Step 1:

Select an initial solution π^0, initialize the best unperformed move Z^* corresponding solution π^0, and empty the tabu list associated with the currently best permutation T^*.

The initial permutation π^0 can be reached as follows: as shown in Figure 3, jobs of sets {*LF+RH+CAS*} followed by {*LF+RH*} are processed in converter 1, then jobs processed in converter 1 are transported by crane 1 in span 1 to LF refining settled in span 1. The transportations from LF refining to RH refining are executed by crane 1 in span 1 too. The transportation of jobs {*LF+RH+CAS*} from RH refining to CAS refining is executed by crane 2 in span 1. Jobs of sets {*RH+LF*} followed by {*LF*} are processed in converter 2, and then jobs processed in converter 2 are transported to span 2. Jobs of sets {*CAS*} followed by {*RH*} are processed in converter 3, and then jobs processed in converter 3 are transported by crane 2 in span 1. We choose to settle jobs in those refining furnace with smaller total completion time if two refining furnaces are available.

Step 2:

Generate a permutation from the neighborhood of π^i by interchanging two jobs of the same type processed in the same convert to reach local optimal solution, such that the move is not in the tabu list or satisfies aspiration condition, then refresh tabu list and π^i.

If the move is in the tabu list and does not pass the aspiration, then select another move. The new permutation is obtained by inserting one job of set {*LF+RH*}, {*LF*} or {*RH*} processed in one converter to another, as shown in figure 2.

Step 3:

If the stopping criterion is fulfilled, STOP. Else if, go to Step 2.

In the following section, we give the computational results which show the tabu search algorithm is efficient relative to sequenced and separately algorithm and the lower bound. In sequenced and separately algorithm which is always used in production face, LPT(Largest Processing Time first) strategy of all jobs is used to minimize the makespan for parallel machine problem, and then jobs are transported by those available transporters to available refining furnaces downstream. Denote the function value found by sequenced and separately one C^S, and the function value found by coordinated algorithm C^{TS}. Then, the relative improvement from separated Algorithm to the coordinated approach is defined as C^S/C^{TS}. The lower bound of the problem is shown as follows:

$$
\begin{aligned}
C^{LB} = \max\{ & 2t + \left(\sum\nolimits_{j\in\{LF,LF+RH,LF+RH+CAS\}} P_j^1 + \sum\nolimits_{j\in RH+LF} P_j^2\right)\Big/2, \\
& 2t + (\sum\nolimits_{j\in\{RH,RH+LF\}} P_j^1 + \sum\nolimits_{j\in\{LF+RH,LF+RH+CAS\}} P_j^2)\Big/3, \\
& 2t + (\sum\nolimits_{j\in LF+RH+CAS} P_j^3 + \sum\nolimits_{j\in\{CAS\}} P_j^1)\Big/2, \\
& \sum\nolimits_{j\in N} P_j^0\Big/3 + 2t + \min\nolimits_{j\in\Omega}\{P_j^1\}\}
\end{aligned}
\tag{11}
$$

Then the relative improvement from tabu search algorithm to the lower bound is defined as C^{TS}/C^{LB}.

All the algorithms were programmed in *C* language and run on a PC with Pentium-Ⅳ (2.40 GHz) CPU using the windows XP operating system. We consider job processing times in refining furnaces P_j^1, P_j^2, P_j^3 were generated the discrete uniform distribution [10, 30] respectively. The transportation time t was generated from the discrete uniform distribution [2, 5]. The transportation time t' from RH refining to CAS refining in span 1 and transportation time from LF refining to RH refining in span 2 are both 1. The number of each type of jobs were generated the discrete uniform distribution [a, b].

Based on the analysis of solution quality in Table 1 and Table 2 the following observations can be made:

(1) The results indicate that the coordinated tabu Search algorithm gives much better function value compared to the practical algorithm function value, and the gap between tabu search algorithm and lower bound is small.
(2) There is no obvious improvement from separated algorithm to the coordinated approach as a/b changed, while the solution quality improves as the job number increases for given a/b. The solution quality from tabu search algorithm to lower bound improves as job number and a/b increase.
(3) There is no obvious improvement from random processing time in converters to those constant processing time because there are seldom idle times in converters for both random processing time and those constant processing time in given algorithms.

5. WORST CASE ANALYSIS

We note that the solution quality obtained from random processing time is no worse than those constant processing time as shown in computational results, thus in the following section, we provide the worst case analysis for constant processing time in converters for simplifying the problem.

Theorem: The worst case ratio of the tabu search algorithm must be no more than 6 if job processing times in converters are constant, and furthermore, no more than 3 if the number of each type of jobs no more than a quarter of total jobs number can be satisfied too.

Proof: Without loss of generality, we denote P^0, $P^0 \in [30, 40]$, as the processing time in converters of all jobs and thus there is no cranes conflict in initial solution. Denote n' as $N_{LF+RH+CAS}$ and P^i as the maximum processing time in the i-multiple refining of all jobs. Note that $P^i < P^0$ and $4t < P^0$ for $P^i \in [10, 30]$ and $t < 5$. For LF+RH+CAS jobs taken from the input queue according to initial permutation, we index them as $1, 2, \cdots, n'$. We conclude that the maximum completion time

Table 1 : Average optimality gaps of the separated algorithm with respect to the coordinated approach (100%)

C^S/C^{TS}	$P_j^0 \in [30, 40]$	$P_j^0=30$	$P_j^0=35$	$P_j^0=40$
a =10, b =40	2.3124	1.4961	1.8946	2.4082
a =30, b =120	1.3886	1.0997	2.1479	2.0689
a =50, b =200	1.1966	1.7771	1.4477	1.7033
a =10, b =30	2.1856	2.3824	1.6347	1.9737
a =30, b =90	1.6182	2.2377	1.4625	2.1483
a =50, b =150	1.1039	3.3377	1.0021	1.7308
a =10, b =20	2.5887	1.8825	2.4056	2.193
a =30, b =60	2.1262	1.8118	2.1563	2.2124
a =50, b =100	1.9299	1.6634	2.1798	1.8185
a =40, b =60	2.0335	2.2137	2.1009	1.9665
a =60, b =80	1.3774	1.4716	1.3782	1.3629
a =80, b =100	1.3957	1.3058	1.6988	1.4154
a =100, b =120	1.3676	1.3521	1.3584	1.3401
a =120, b =140	1.5340	4.1222	2.6631	1.6216
a =140, b =160	1.4593	1.1874	1.3655	1.0443

Table 2 : Average optimality gaps of the lower bounds with respect to the coordinated approach (100%)

C^{TS}/C^{LB}	$P_j^0 \in [30, 40]$	$P_j^0=30$	$P_j^0=35$	$P_j^0=40$
a =10, b =40	1.3326	1.3515	1.2983	1.0730
a =30, b =120	1.4010	1.3058	1.1136	1.3927
a =50, b =200	1.2580	1.2929	1.5179	1.1895
a =10, b =30	1.2086	1.1182	1.2643	1.3001
a =30, b =90	1.2496	1.0979	1.2326	1.0637
a =50, b =150	1.2652	1.2674	1.4523	1.2607
a =10, b =20	1.0920	1.0779	1.1351	1.2122
a =30, b =60	1.0890	1.0839	1.0828	1.1651
a =50, b =100	1.0774	1.0799	1.0771	1.1825
a =40, b =60	1.0712	1.0309	1.0934	1.1436
a =60, b =80	1.0499	1.0526	1.0714	1.0537
a =80, b =100	1.0694	1.1008	1.1065	1.0598
a =100, b =120	1.0491	1.0223	1.0541	1.0525
a =120, b =140	1.0599	1.0412	1.0393	1.0586
a =140, b =160	1.0504	1.0217	1.0568	1.0484

of those jobs which steelmaking operation occurred in converter 1 is no more than

$$\begin{aligned} &P^0+\max\left\{P^0,P^1+4t\right\}+\max\left\{P^0,\max\left\{P_1^2+1,2t+P^1\right\}+2t\right\} \\ &+\cdots+\max\left\{P^0,\max\left\{P_{n'-2}^2+1,2t+P_{n'-1}^1\right\}+2t\right\}+P_{n'}^2+1+P_{n'}^3 \\ &+\sum\nolimits_{j\in LF}P^0+(N_{LF}-1)4t+4t+P^1 \\ &\le\sum\nolimits_{j\in LF+RH+CAS}P^0+(n'-1)4t+P^2+1+P^3 \\ &+\sum\nolimits_{j\in LF}P^0+(N_{LF}-1)4t+4t+P^1 \end{aligned} \tag{12}$$

Similarly, the maximum completion time of those RH+LF and LF jobs which have been processed in converter 2 is no more than

$$\begin{aligned} &\sum\nolimits_{j\in RH+LF}P^0+(2t+1)N_{RH+LF}+P^2-1 \\ &+\sum\nolimits_{j\in LF}P^0+(N_{LF}-1)4t+2t+P^1 \end{aligned} \tag{13}$$

The maximum completion time of those RH+LF and LF jobs which is processed by converter 3 for their steelmaking processing is no more than

$$\sum\nolimits_{j\in CAS}P^0+2tN_{CAS}+P^2+\sum\nolimits_{j\in RH}P^0+2tN_{RH}+P^2. \tag{14}$$

Thus,

$$\begin{aligned} C^H\le\max\{&2P^0(N_{LF+RH+CAS}+N_{LF+RH}),2P^0(N_{RH+LF}+N_{LF}), \\ &2P^0(N_{CAS}+N_{RH})\} \end{aligned} \tag{15}$$

It is well known that $\sum_{j=1}^{N}P_j\Big/3$ is a lower bound for three machines parallel problem, thus $\sum_{j\in N}P^0\Big/3+2t+\min_{j\in\Omega}\left\{P_j^1\right\}$ is a lower bound for the problem described in this section obviously, It follows that

$$\begin{aligned} \frac{C^H}{C^*}&\le\max\{2P^0(N_{LF+RH+CAS}+N_{LF+RH}),2P^0(N_{RH+LF}+N_{LF}), \\ &\qquad 2P^0(N_{CAS}+N_{RH})\}/\sum\nolimits_{j\in N}P^0\Big/3+2t+\min_{j\in\Omega}\left\{P_j^1\right\} \\ &\le\max\{2P^0(N_{LF+RH+CAS}+N_{LF+RH}),2P^0(N_{RH+LF}+N_{LF}), \\ &\qquad 2P^0(N_{CAS}+N_{RH})\}/\sum\nolimits_{j\in N}P^0\Big/3\le 6 \end{aligned} \tag{16}$$

Where C^* is the optimal solution value of the problem. Thus, we conclude that the makespan of tabu search algorithm may be 6 times that of an optimal schedule for constant processing time in converters. Furthermore, it can be easily reached that the worst case ratio may reach 3 if the number of each type of jobs no more than a quarter of total jobs number is satisfied too.

6. CONCLUSIONS

In this study, steelmaking and multi-refining scheduling problem with trolleys and cranes transportation consideration has been addressed. Mathematical model are abstracted from the production fact firstly, and then a tabu search algorithms are proposed for the model, finally, we provide the computational results which show the average relative improvement from coordinated approach to sequence and separately algorithm and bound. We also prove the tabu search algorithm can provide a worst case ratio no more than 3 in practice.

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