**Two-Stage Method and Application for Molten Iron Scheduling Problem between Iron-Making Plants and Steel-Making Plants**

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**Abstract:** In this paper, a two-stage method is proposed to solve the molten iron scheduling problem (MISP). Firstly, a 0-1 mixed-integer nonlinear programming model is established for special type of molten iron scheduling problem (STMISP). A method to solve mathematical model of STMISP is presented, which include assigning machine strategy of STMISP and determining mathematical model of eliminating machine conflicts. Secondly, on the basis of results of STMISP, a heuristic algorithm based on the rule of first come first serve (FCFS) principle is established to solve normal type of molten iron scheduling problem (NTMISP). The molten iron scheduling system with the two-stage method has been successfully applied to Shanghai Baosteel Company to realize quickly optimal molten iron scheduling. Application results show that the two-stage method is both effective and feasible.

**Keywords:** Molten iron scheduling problem, Two-stage method, Hybrid flow shop, Mixed-integer nonlinear programming model, Heuristic algorithm.

1. INTRODUCTION

In the iron-making stage, molten iron is smelted from iron ore, limestone and bituminous coal in blast furnaces and then poured into pots carried on torpedo cars (TPC). These torpedo cars are driven by locomotives through a rail-track network to steel-making plants. Molten iron logistics is composed of production, transportation, processing and usage. The logistics includes three processing stages, namely receiving iron, molten iron pretreatment and relading (RL). The processing stage of molten iron pretreatment includes a number of stages such as pre-processing (PR), desulphurization and dephosphorization (SP), and post-processing (PO). The operational state of molten iron logistic process affects the production of large equipments, such as blast furnaces in iron-making plants and converter furnaces in steel-making plants.

Molten iron scheduling determines the processing route, the equipment in all processes and starting times in all equipments of pots of the molten iron. This process generates a schedule plan ensuring continuous and stability production. At present, molten iron scheduling system of Shanghai Baosteel Company has realized information management albeit molten iron scheduling is still accomplished by manual operation, where the performance of molten iron scheduling relies heavily upon the experiences of the scheduler who can only schedules one pot of molten iron at a time. As a result, the schedule plan of all pots is impossibly generated from the overall perspective in the planning time window. Therefore it is necessary to develop rational and effective solution method of MISP.

Most of the previous work for iron and steel industry (e.g., Lixin Tang et al., 2010, Arezzo Atighehchian et al., 2009, A. Bellabdaoui and J. Teghem, 2006) have focused on scheduling steel-making and hot rolling operations rather than addressing molten iron scheduling issues. Only a few literatures focused on the molten iron transport scheduling problem and for example Gongshu Wang and Lixin Tang (2007) developed a mix integer programming model for locomotive scheduling problem. Qiu et al. (2003) established the mathematical models for solving molten iron supply and management and locomotive transportation issues. Cui et al. (2003) established a molten iron transport simulation system, where a locomotive model was developed, and molten iron route selection and automatic collision avoidance algorithms for molten iron transportation are realized. Some literatures studied the molten iron allocation problem. Lixin Tang et al. (2007) formulated the molten iron allocation problem as an integer programming model. Wang et al. (2009) established a model for solving the molten iron preparation problem. The model is solved through two level methods. Gomes D A et al. (2008) proposed an optimization approach to deal with the scheduling of torpedo cars. The above works studied the locomotive scheduling problem and molten iron allocation...
problem. However, the focus was not on the molten iron scheduling problem. Due to the complexity of MISP, research into the MISP has not only theoretic value, but also practical potentials. It plays an important role in increasing production efficiency and reducing production cost.

2. MOLTEN IRON SCHEDULING PROBLEM DESCRIPTION

2.1 Molten iron logistic process

Molten iron logistics process is composed of three stages, namely receiving iron, molten iron pretreatment and reladling (Fig.1). In the process of receiving iron, molten iron produced from blast furnaces is loaded by TPC. Molten iron in TPC is called a Pot. A production process on equipment is called Unit. Secondly, in the process of molten iron pretreatment, it includes some processes, such as pre-processing, desulphurization, dephosphorization and post-processing. The aim of pre-processing is to remove iron slag and impurities in the surface of molten iron inside the torpedo tanks. In the desulfurization stage, the process of desulfurization and dephosphorization is completed by simultaneously injecting desulfurizer and dephosphorizer into molten iron of pots. After desulphurization and dephosphorization, iron slag and impurities would emerge on the surface of molten iron. In order to meet the quality requirements of steel-making on the molten iron, molten iron needs to be treated by post-processing. In the last process of reladling, molten iron of pots is dumped into ladles after torpedo cars arriving at the reladling station.

Unlike general production scheduling in the machinery industry, MISP has to meet special requirements of molten iron logistics process. In the MISP, the products (i.e. molten iron) being processed are handled at high temperature and are loaded by TPC passing through the logistics process of production, transportation, processing and usage. There are extremely strict requirements on material continuity and flow time. Secondly, the processing route of pots is related to molten iron composition. The pots of special type of molten iron have complete processing route. The processing route of the pots of normal type of molten iron is determined in operation. Since molten iron is continuously processed at high temperature, there are no stocks in MISP. Increase of waiting time means that temperature of molten iron will decrease, which will cause the waste of energy and the increase of production costs.

2.2 Molten iron scheduling problem

MISP is a production schedule problem that highly demands the processing and transportation time, weight, component and temperature with multi-stages, multi-production lines, multi-processes and the use of multi-machines. MISP is that: taking a pot as a job, on the condition of techniques restriction, it is to ensure that molten iron of pots is sent to steel plants according to the indices of molten iron, such as time, weight, composition, temperature and so on. The purpose is to optimize two objectives: namely to minimize tardiness time of pots at reladling stage and the waiting time of pots at all stages. In this context, molten iron scheduler...
determines in what sequence, at what time and on which device molten iron should be arranged at various logistics stages from receiving iron to reladling.

As it can be seen from Fig.1, molten iron logistics process has both the features of parallel flow shop and hybrid flow shop. At the molten iron pretreatment and reladling stages, there are two parallel production lines. In addition, there are many parallel devices in various processes of each production line. Therefore, the MISP is neither parallel flow shop scheduling problem, nor is hybrid flow shop scheduling problem. It is called parallel hybrid flow shop scheduling problem (PHFSSP) in this paper. The solution to PHFSSP is not only to determine jobs processed in each production line, but also to determine on which device jobs should be arranged in various processes of each production line, and then to determine processing sequence and the start time of jobs in various units. Since the parallel flow shop and hybrid flow shop scheduling problem have been proved to be NP-hard problem, it is clear that the PHFSSP is also a NP-hard problem.

With reference to the solution steps of parallel flow shop scheduling problem, the procedure for solving PHFSSP can be divided into two steps. In the first step, the jobs are allocated to each production line, where the production sequence of jobs is determined. In the second step, the devices of jobs are determined in various processes of each production line, and the production time of jobs is determined. Therefore, the procedure for solving MISP is accordingly divided into two steps. Firstly, the processing route of molten iron is determined in accordance with the indices of molten iron, such as time, weight and composition etc. Secondly, the production devices and processing time of pots of molten iron are determined, thus the scheduling plan of pots of molten iron is generated. This paper will focus on the second step. MISP can be simplified as hybrid flow shop scheduling problem after determinning molten iron routing process. In addition, as the capacity of pre- and post-processing machines is finite, the process paths of pots of molten iron are subjected to uncertainties. Therefore, the difficulty of MISP is further increased.

3. TWO-STAGE METHOD FOR MISP

MISP can be solved in two stages according to the different compositions and types of molten iron. Molten iron can be divided into two categories according to their component types. One of categories is the special composition type of molten iron, such as silicon steel type of molten iron and demanganization type of molten iron. Another category is normal composition type of molten iron. Special composition type of molten iron has high production quality requirement and high production priority. It must be processed by all the processes, so it needs to be scheduled firstly. As processing capacity of pre-processing and post-processing machines is finite, the normal composition type of molten iron may be not processed by either pre-processing or post-processing machines. Whether normal composition type of molten iron is processed by pre-processing machines or post-processing machines is determined by the state and residual capacity of pre-processing and post-processing machines. This means that the solution to the MISP is very difficult. In addition, on the molten iron production site, the requirements of real-time scheduling is very high, the average response time of obtaining scheduling plan is 10 seconds. This paper presents a two-stage method to solve MISP. Firstly, a 0-1 mixed-integer nonlinear programming model is established for STMISP, and a method including assigning machine strategy and eliminating machine conflicts is presented to solve the model of STMISP. Secondly, on the basis of results of STMISP, a heuristic algorithm based on the rule of FCFS is established to solve NTMISP.

3.1 Mathematical model and solution method of STMISP

The following symbols are used to define the problem parameters and decision variables.

**Parameters**

\[ M_j \] the total number of parallel machines of unit \( j \);

\[ m_i \] the initialization unit number of charge \( i \), \( m_i \leq m \);

\[ p_{ik} \] the processing time of pot \( i \) on machine \( k \) of unit \( j \);

\[ c_{ik} \] the transportation time of pot \( i \) from the machine of unit \( j \) to the machine of unit \( j+1 \);

\[ e_{jk} \] the end time of pot \( i \) on the machine \( k \) of unit \( j \);

\[ S(i,j,k) \] the immediate successor pot of pot \( i \) processed on the machine \( k \) of unit \( j \);

\[ T^w_i \] the target starting time of pot \( i \) on the machine of reladling unit;

\[ T^{wr}_i \] the starting time of pot \( i \) on the unit of receiving iron;

\[ C_{ij} \] the coefficient of penalty cost for the waiting time of pot \( i \) after finishing process on the machine \( k \) of unit \( j \);

\[ C_{2ij} \] the coefficient of penalty cost for the processing of pot \( i \) being late with respect to the targeted starting time of pot \( i \) on the machine of reladling unit;

\[ l \] the number of the intervals of equipment available time, \( 1 \leq l \leq d_k \), where \( d_k \) is the total interval number of equipment available time;

\[ US_{kl} \] the starting time of the \( l \)th interval of available time of machine \( k \);

\[ UE_{kl} \] the end time of the \( l \)th interval of available time of machine \( k \);

\( U \) a sufficiently large positive integer.
**Decision variables**

\( x_{ijk} \) the variable of model denotes the starting time of pot \( i \) on the machine \( k \) of unit \( j \),

\( y_{ijk} \) 1 if pot \( i \) is arranged on the machine \( k \) of unit \( j \), 0 otherwise.

Using the above notations, the MISP can be formulated as the following 0-1 mixed-integer nonlinear programming model.

\[
\begin{align*}
\text{Min} & \sum_{i=1}^{n} \sum_{j=1}^{M} \sum_{k=1}^{M} C_{1_{ijk}} (x_{ij(k+1)} - x_{ijk} - p_{ijk} - t'_{j,ijk}) \\
& + \sum_{i=1}^{n} \sum_{j=1}^{M} \sum_{k=1}^{M} C_{2_{ij}} (x_{ijk} - T'_{ij}) \\
S.T. & \\
\sum_{k=1}^{M} y_{ijk} = 1 & i = 1, \ldots, n; j = 1, \ldots, m \\
\sum_{j=1}^{M} y_{i jk} = x_{ijk} y_{ijk} + pt_{ijk} y_{ijk} & i = 1, \ldots, n; j = 1, \ldots, m; k = 1, \ldots, M \\
x_{5k(i, j, k)} y_{5k(i, j, k)} + U (2 - y_{ij(k+1)}) y_{ij(k+1)} & \geq 0 \\
i, s(i, j, k) = 1, \ldots, m; j = 1, \ldots, m; k = 1, \ldots, M \\
x_{ij(k+1)} y_{ij(k+1)} = U (2 - y_{ij(k+1)}) y_{ij(k+1)} & \geq t'_{j,ijk} \\
i, j = 1, \ldots, n; j = 1, \ldots, m; k = 1, \ldots, M \\
x_{ij} \leq x_{ij} \leq U e_{ij} & i = 1, \ldots, n; j = 1, \ldots, m \\
x_{ijk} = T'_{ij} & j = 1; k = 1, \ldots, M \\
x_{ijk} \geq 0 & i = 1, \ldots, n; j = 1, \ldots, m; k = 1, \ldots, M \\
y_{ijk} \in \{0,1\} & i = 1, \ldots, n; j = 1, \ldots, m; k = 1, \ldots, M \\
\end{align*}
\]

In the formulation, objective (1) is composed of two terms: the pot waiting time and the penalty of tardiness time. Constraint (2) ensures that each pot can only be arranged into a unit at the same time. Constraint (3) guarantees that operation processing cannot be interrupted. Constraint (4) ensures that for two contiguous pots processed on the same machine, the immediately next one can be started only when the preceding pot is finished. Constraint (5) means that for contiguous operation of the same pot, only when the preceding operation is completed and the pot is transported to the next machine, the immediately next operation on the pot can be started. Constraint (6) ensures the processing time of pot must be within the interval of available time of machines. Constraint (7) indicates that the starting time of pots processed at receiving iron stage must be set according to the actual time, and are set as constant.

**3.1.2 Method to solve mathematical model of STMISP**

For solving the mixed integer nonlinear programming model of STMISP, the method includes two parts.

1. Assigning machine strategy of STMISP

The problem of machine assignment of STMISP can be described as this: based on the starting time of pots processed at the receiving iron stage, assign \( n \) pots to \( m \) units and find the optimal production path. In other words, assign each pot to all the machines, and determine the processing sequence of each pot in the same machine. The aim is to ensure the conflicting time on each machine minimum so as to obtain a better initial schedule. The core of assigning machine strategy is how the machine can be chosen for the pot when there are other pots assigned at the corresponding time periods in each unit.

![Fig. 3. The types of time conflict on machines](image)

**The types of possible time confliction on machines**

The types of possible time confliction on machines are shown in Fig. 3. To describe the assigning machine strategy, we first define the confliction function as follows:

\[
f_j(i, r, k) = \begin{cases} 
\min \{ et_{ij}, et_{ijk} \} - \max \{ x_{ij}, x_{ijk} \}, & \text{if } x_{ij}, x_{ijk} \\
0, & \text{otherwise}
\end{cases}
\]

The total processing time of conflicts is \( \sum f_j(i, r, k) \) on machine \( k \). Symbol \( r \) represent that the pots have been assigned to machine \( k \) of unit \( j \). The assigning machine strategy includes the following four steps.

Step1: Select machine \( k \) that can process \( x_{i,j,k} \) unit and has the smallest total of conflicts time \( \min \{ \sum f_j(i, r, k) \} \).

Step2: If machine \( k \) is more than one, choose machine \( k \) which has the least equipment load to balance the equipment load of each machine.

Step3: If machine \( k \) is not only one, select machine \( k \) to make \( f'_{j,i,j} \) the smallest by the short route rule \( \min f'_{j,i,j} \).

Step4: If machine \( k \) is still not the only one, randomly select a machine \( k \), and stop.

(2) Mathematical model of eliminating machine conflicts

After assigning machine, there may exist many conflicts among processing machines. In order to make the initial scheduling becomes feasible, the model of STMISP is transformed here to eliminate machine conflicts.

The 0-1 variable \( y_{ijk} \) of the model of STMISP was solved by assigning machine strategy. The transportation time \( t'_{j,i,j+1} \) and processing sequence of pots are determined. Then, constraint (3), (4) and (5) can be expressed as follows:

\[
\begin{align*}
\text{et}_{ijk} = x_{ijk} + pt_{ijk} & i = 1, \ldots, n; j = 1, \ldots, m; k = 1, \ldots, M \\
x_{5k(i, j, k)} et_{ijk} \geq 0 & i, s(i, j, k) = 1, \ldots, m; j = 1, \ldots, m; k = 1, \ldots, M \\
\end{align*}
\]
Under the assumption of no changing processing sequence of pots, the mixed integer nonlinear programming model of STMISP can be simplified to give:

$$\text{Min } (1)$$

$$\text{S.T. } (6)-(9),(11),(12),(13)$$

It can be seen that the above eliminating machine conflicts can be solved using the well-known linear programming (LP) method.

### 3.2 Heuristic algorithm of NTMISP

Since the capacity of pre- and post-processing machines is finite, not all of pots of normal type of molten iron can be handled by the pre- and post-processing machines in the planning cycle. Thus only part of pots of normal type of molten iron can be processed. Which pot of molten iron can be processed is determined by whether there is idle machine when it arrives at the pre- or post-processing process. Therefore, pots of normal type of molten iron are required to be determined for their treatment paths in the scheduling process. Meanwhile, the processing machine and the start and end times of the machine in each process are determined.

By summarizing the practice experience of molten iron scheduler, this paper presents a heuristic algorithm based on the rule of first come first serve (FCFS) bases to solve the scheduling problem of normal type of molten iron. The algorithm is as follow.

**Step1:** In the planning cycle, the pots of normal type of molten iron are arranged in accordance with the order of receiving iron, pre-processing, desulphurization, post-processing and reladding.

**Step2:** Compute the start/end time of pots in all machines of the current process, and sort the scheduling according to the start time of pots in each machine.

**Step3:** Select the pot with the earliest start time in all machines of current process, compute conflict time between operation time of the pot and maintenance time of the machine, and between operation time of the pot and available time of the machine. If there is a conflict, the start time of the pot on the current machine is adjusted according to the conflict time.

**Step4:** Calculate the conflict time between the operation time of the current pot and those of other pots that have been arranged on the current machine. If there is a conflict, the current pot is scheduled in accordance with the rule of FCFS, and judge the type of the current process. If the current process is either desulphurization or reladding process, go to step 5; otherwise, go to step 6.

**Step5:** Judge the type of the conflict, if it is a hind conflict, the operation time of current pot is adjusted backward. If it is a fore conflict, and the conflict time is longer than the allowable waiting time, the operation time of current pot is adjusted backward. If it is a fore conflict, and the conflict time is less than allowable waiting time, the operation time of the conflict pot is adjusted backward.

**Step6:** Judge the type of the conflict, if it is a hind conflict, and the conflict time is longer than the allowable waiting time, then the current pot does not select the current machine. If the conflict time is less than the allowable waiting time, then the operation time of the current pot is adjusted backward. If it is a fore conflict, and the conflict time is longer than the allowable waiting time, the current pot does not select the current machine. If the conflict time is less than the allowable waiting time, then the operation time of the conflict pot is adjusted backward.

**Step7:** After above adjustment on the operation time of the current pot, if the current pot does not give up selecting machine of the current process, then we select the machine in which the start time of current pot is the earliest in the current process. Meanwhile the operation time of the current pot in this machine is determined. If the current pot gives up selecting all machines of current process, then the next pot is scheduled according to Steps 2-7.

**Step8:** Check whether all pots have been arranged in the current process. If they are, go to Step 9. Otherwise, go to Steps 2-7 and schedule other pots.

**Step9:** Schedule the next process according to Steps 2-8. Stop until all pots of normal type of molten iron have been arranged in all processes.

### 4. APPLICATION

#### 4.1 Background

The Shanghai Baosteel Company of China is a large iron and steel enterprises. The treatment process of molten iron in this company is comprehensive and includes all kinds of typical treatment processes of molten iron. Baosteel Company has large molten iron treatment equipments and processes of molten iron.

#### 4.2 System development and application results

Based on the optimal two-stage method presented in the paper, the molten iron scheduling system software is developed using the integrated development environment of Microsoft Visual Studio.NET 2008. The mathematical model and algorithm are developed using C++, and the system application interface is developed using C# language. ORACLE 10g is used for the database software of system.

An example from practical production data on 04/16/2009 is used to show the effectiveness of the proposed two-stage method. There are 36 pots that need to be arranged, including 6 pots of special type of molten iron, 30 pots of normal type of molten iron. After assigning machine, the initial scheduling results of pots of special type of molten iron are shown in Table 1, where data with underline are processing machine and the start time of pots of special type of molten iron, which have conflicts on the machine. After eliminating machine conflicts, the scheduling results of pots
of special type of molten iron are shown in Table 2, where data with underline are the processing machine and the start time of pots of special type of molten iron, which have been modified after eliminating conflicts. On the basis of scheduling results of pots of special type of molten iron, pots of normal type of molten iron are arranged. The scheduling results of all pots in the planning cycle are thus obtained.

After a long period of system operation, the application results show that the computing time of molten iron scheduling that used the proposed two-stage method is within 10 seconds. This may satisfy the real time requirement, effectively reduces the work intensity of molten iron schedulers and improves the work efficiency. In addition, the processing rate of pots processed by pre- and post-processing has increased, which means that more pots can be processed by the pre- and post-processing machines. Therefore, the production efficiency of pre- and post-processing machines, and the composition index and quality of molten iron has been improved, which leads to significant economic benefits.

<table>
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5. CONCLUSIONS

A novel two-stage method for MISP between the iron- and steel-making stages is developed in this paper. The molten iron scheduling system based two-stage method has been successfully applied to Shanghai Baosteel Company, where it has been shown that it can realize the optimal molten iron scheduling quickly. Application results show that the two-stage method is both effective and feasible. As a result, significant improvement has been obtained on the production efficiency and the working strength of scheduler. The two-stage method for MISP can also be used in other iron and steel company to reduce the cost of molten iron production and to improve the quality of iron products.

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