Steel-making Schedule of Mixed Whole/Half Charging Plan  
Based on Locked-Path Heuristic Policy

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Abstract: Steel-making and continuous/mould casting are the key processes of modern iron and steel enterprises. The continuous and mould casting schedule of mixed whole/half charging plan is the bottleneck for the steel-making and continuous/mould casting process. However, it is very difficult to find a solution against the characteristics and complicated environment. This paper proposed a heuristic batch splitting schedule policy. Based on the complex constraints for this process, we established a model of continuous and mould casting schedule of mixed whole/half charging Plan. The model is solved by heuristic algorithm. Numerical testing supported by Shanghai Bao steel plant demonstrated that the method could realize the production cycle reduction and be more efficient to assist scheduler to make a steel-making and continuous casting scheduling which could realize the high production.

1. INTRODUCTION

With the drastic competition in iron & steel industry, how to effectively implement multi-varieties and small-batch production, realize high quality, low price, delivery on time and better after sale services are becoming more and more important. In iron & steel enterprises, steel-making & continuous casting are the key processes of the steel-making flow. Scheduler not only need to consider the problems about material balance and resource balance, but also need to consider the problem about time balance between every process existed in production process. So how to balance the load of working processes, tightly link up the material flow, reduce the waiting time between working process, highly improve production efficiency, products quality ,production flexibility, decrease the consumption of energy sources and material are becoming the hotspot of research.

Modern iron and steel corporations are moving towards continuous, high-speed and automation with large devices. The focus is placed on high quality, low cost, just-in-time delivery and small lot with different varieties. In order to enhance their competitive power, many international iron and steel corporations are devoted to developing computer integrated manufacturing systems (CIMS) which can improve productivity of large devices, reduce waiting-time between operations, save material and energy consumption, and cut down production costs. Production scheduling is a key component of CIMS. Its task is to determine the beginning time and the completion time of jobs on the machines so that the enterprise realizes the high production.

The liquid iron is first processed by converters, after that, the liquid iron is send to the next process called refining, the operation of this process is to add alloys to the metal to meet the chemical requirements, and the physical properties which are required by the customer. The steel plant processes the molten iron, initially in 300 ton batches called casts. Each cast is processed between 2 and 6 stations, depending on the analysis and the properties requirements of the final product. The casts then go to be casted into solid products of the dimensions required by the user. The solid steel may go through several further treatments to improve its surface or internal properties: these may take from a few minutes to two weeks to complete.

Casting is a semi-continuous process, i.e. a cast must arrive at the casting machine timely just as the previous cast completes casting, so as to continue the sequence of casts. However, sequences can only contain casts of similar chemical constituents and cross-section, therefore breaks in the casting process must be scheduled to allow production of casts of different sizes and chemical constituents.

Steel-making and continuous casting (SCC) production scheduling problems are to determine in what sequence, at what time and on which device molten steel should be arranged. Unlike general production scheduling in machinery industry, SCC production scheduling problems have to meet special requirements of steel production process. During recent years, the continuous casting technology, which is developed in the 1950s, undergoes a rapid growth. Because the continuous casting technology can save more energy consumption in the production process from hot steel to slab, the main steels are produced by continuous casting, but mould casting is still useful. Some-category steels can only be produced by mould casting. For example: the US army requests that some steels must be produced by mould casting, not continuous casting; the mould casting can increase sales volume, improve logistics balance and increase in equipment utilization; the unqualified molten steel can be used by mould casting. For example, some molten steel that continuous caster can’t pour can be poured to capped steel. So the schedule of
steel-making and continuous casting & mould casting is very important.

2. LITERATURE REVIEW

Redwine and Wisme (1974) provided an example of off-line scheduling for steel production using mathematical programming. Dynamic programming was used to solve the model. Petersen et al. (1992) have developed a mathematical programming model for a steel production scheduling problem to optimally schedule the slabs through the reheating furnace and the rolling mill. The model was solved heuristically. Lally et al. (1987) established a simple mixed-integer linear programming solution to the problem of caster scheduling. They considered a simple model of a steel plant in which steel was started at an electric arc furnace, held in a ladle, and cast on a continuous caster. However, the model did not consider all the complexities of a real continuous caster.


Joseph D. Blackburn and Robert A. Millen (2007) examined the impact of a rolling-schedule implementation on the performance of three of the better known lot-sizing methods for single-level assembly systems. Chandrasekharan Rajendran (1993) made a heuristic algorithm which was presented for scheduling in a flowshop to minimize the total flowtime of jobs. The heuristic preference relation was developed and used as the basis for job insertion to build up the complete schedule. Rainer Kolisch and Sonke Hartmann (2006) considered heuristics for the well-known resource-constrained project scheduling problem (RCPSP). They summarized and categorized a large number of heuristics that had recently been proposed in the literature. MMost of these heuristics were evaluated in a computational study and compared on the basis of standardized experimental design. Peter I. Cowling et al. (2003) proposed a multi-agent architecture for integrated dynamic scheduling of the hot strip mill (HSM) and the continuous caster.

3. THE DESCRIPTION OF HEURISTIC POLICY

To describe the continuous/mould casting production process, we first introduce the following special terms:

Work station: In one operating procedure, the work station means the operation time of a charge plan in a certain kind of steel-making equipment. A charge plan includes several work stations.

Charge: The process of a ladle of molten iron from converter to refinery and continuous/mould casting. It contains several units, like job, etc.

Process: The stage number of steel-making, contains converter, refinery and continuous/mould casting. A process may contain several work stations.

Path: The order of each unit work station.

Whole-charge plan: The no-started continuous casting plan.

Half-charge plan: The continuous casting plan which is already processed.

CAST_LOT: A set of charges which have the same chemical composition order by descending width form.

CAST: A set of CAST_LOT which have the same chemical composition and rule of continuous casting batch is in descending sequence of width.

Heuristic batch splitting scheduling policy is divided into half-charge batch and whole charge batch which are based on actual production. Below is the realization of batch splitting scheduling policy of continuous casting plan and mould casting plan.

\[ T_{now} \] is the current time; \( H_f \) is the set of half-charge plan, \( W_f \) is the set of whole-charge plan, \( H_f \subseteq \Omega \cup \Omega' \), \( W_f \subseteq \Omega \cup \Omega' \), \( f=0 \) mean deadline mould casting charge, \( f=1 \) continuous casting charge, \( f=2 \) mean no-deadline mould casting charge.

Step1: The measurement criterion of charge plan’s production state is current time \( T_{now} \). We take the charges that have produced but haven’t cast as half-charge. These charges form a set \( H_f \).

Step2: Eliminate the set of half-charge in the first batch, we take the charges that haven’t produce as whole charge plan according to current time \( T_{now} \). Towards newly increased
charge plan we also take them as whole charge plan. The both form a batch set $W_f$.

Step3: According to the continuous casting, deadline mould casting and no deadline mould plan, we proceed the twice batch splitting that divide the half charge set $H_f$ into set $H_0, H_1$ and $H_2$.

Step4: Whole charge batch also splitting into $H_0, H_1$ and $H_2$.

Step5: There is limitation to start casting time of newly compiled plan in order to realize the cohesion of existing continuous casting and the former. There is limitation to start casting time of deadline mould plan, so the continuous casting should make the best to satisfy. There is no limitation to no-deadline mould plan.

4. MATHEMATICAL MODEL

4.1 Parameters

$S(i,j,k)$: The charge after process $j$ of charge $i$ processed on equipment $k$;

$m_i$: The total work station amount of charge $i$;

$m_i^k$: The initial work station number of charge $i$, $1 \leq m_i^k < m_i$;

$K$: The total amount of equipments;

$K_j$: The parallel machine number of work station $j$;

$\Omega$: The set of waiting continuous casting charge $i \in \Omega$, $|\Omega|$ is the total amount of continuous casting charge;

$\Omega_n$: The set of continuous casting batch $\text{Cast}$; $\Omega_1 \cap \ldots \cap \Omega_n = \Phi, \Omega_1 \cup \ldots \cup \Omega_n = \Omega$;

$\Omega_{first}$: The first charge set of continuous casting batch $\text{Cast}$;

$P_n$: The charge amount of $\Omega_n$;

$\Omega^*$: The set of no-producing mould casting charge; $|\Omega^*|$ is the total amount of mould casting charge;

$\Omega_{n}^*$: The set of mould casting batch $\text{Cast}$ $n$; $\Omega^* \cap \Omega_n = \Phi, \Omega_1^* \cap \ldots \cap \Omega_n^* = \Phi, \Omega_1^* \cup \ldots \cup \Omega_n^* = \Omega^*$;

$R_n^*$: The set of deadline mould casting, $R_n^* \subset \Omega^*$;

$R_n^*$: The set of no-deadline mould casting, $R_n^* \subset \Omega^*, R_n^* \cup R_n^* = \Omega^*$;

$\Theta_i$: The work station set of processing-charge $i$, $i \in \Omega \cup \Omega^*$;

$\Theta_i'$: The work station set of no-processing-charge $i$, $i \in \Omega \cup \Omega^*$;

$pt_{ijk}$: The work station $j$’s standard processing time of charge $i$ processed on equipment $k$;

$ut_{j,j+1}$: The standard transportation time between work station $j$ and work station $j+1$ of charge $i$;

$st_{ijk}$: The work station $j$’s processing start time of charge $i$ processed on equipment $k$;

$et_{ijk}$: The work station $j$’s processing end time of charge $i$ processed on equipment $k$;

$J_n$: The casting time of continuous casting batch $\text{Cast}$ $n$;

$T_n$: The deadline of deadline mould casting charge $n$;

$adjt_{cast}$: The standard interval time between continuous castings batch $\text{Cast}$;

$adjt_{mould}$: The standard interval time between mould castings;

$\sigma$: The set of assigned charge, $\sigma_{jk}$ is the assigned charge set of work station $j$ processed on equipment $k$, $\sigma = \sigma_{11} \cup \ldots \cup \sigma_{jk}, j=1, \ldots, m, k=1, \ldots, K_j$;

$C_n^1$: The break-casting penalty coefficient of continuous casting batch $\text{Cast}$ $n$;

$C_n^2$: The redundancy time penalty coefficient of charge $i$ between work station $j$ and work station $j+1$;

$C_n^3$: The no-schedule penalty coefficient of continuous casting batch $\text{Cast}$ $n$;

$X_{ijk}$: The work station $j$’s optimizing start time of charge $i$ processed on equipment $k$, the decision variable of model;

$y_{ijk}$: If the work station $j$ of charge $i$ processed on equipment $k$, $y_{ijk} = 1$, else
\[ y_{ijk} = 0; \]
\[ \delta_{(i,j,k) \rightarrow (i',j,k)}: \text{charge } i \text{ and } i' \text{'s time interval of The work station } j \text{ and equipment } k. \]

4.2 The Model Formulation

A. Mixed half-charge planning and scheduling model of continuous and mould casting

Half-charge planning adjustment keeps processing equipment \( y_{ijk} \) invariant, which is located in nonproducing work station.

Making plan of equipment’s processing starting time \( st_{ijk} \).

Using the above notations, the mathematical model for the Mixed half-charge planning and scheduling problem is formulated as follows:

\[
f(t) = \min_{i=1,j=1,k=1} (st_{ijk} y_{ijk}) \tag{1}
\]

Subject to:

\[
st_{i,m,k} y_{i,m,k} + pt_{i,m,k} y_{i,m,k} = \tag{2}
\]

\[
st_{sl(i,m,k),m,k} y_{sl(i,m,k),m,k}, i \in \Omega
\]

\[
st_{i,m,k} y_{i,m,k} + pt_{i,m,k} y_{i,m,k} + adjt_{mould} \geq \tag{3}
\]

\[
when \ st_{i,m,k} y_{i,m,k} + pt_{i,m,k} y_{i,m,k} + adjt_{mould} \geq
\]

\[
st_{sl(i,m,k),m,k} y_{sl(i,m,k),m,k}, i \in \Omega
\]

\[
et_{ijk} y_{ijk} = st_{ijk} y_{ijk} + pt_{ijk} y_{ijk} \tag{4}
\]

\[
st_{ijk} y_{ijk} + pt_{ijk} y_{ijk} \leq st_{sl(i,j,k),j,k} y_{sl(i,j,k)j,k} \tag{5}
\]

\[
st_{ijk} y_{ijk} + pt_{ijk} y_{ijk} + ut_{j,i+1}^{f} \leq st_{i,(j+1,k)k} y_{i,(j+1,k)k} \tag{6}
\]

\[
s_{i,j,k}, e_{ijk} > T_{n} i \in R^{*} \tag{7}
\]

\[
s_{i,m,k} \geq T_{n}, i \in R^{*} \tag{8}
\]

The objective function represents locking the half-charge planning’s path and only adjust the time to ensure the earlier production of half-charges in batch of continuous casting.

Constraint (2) represents continuous casting. The charges in a same continuous casting must be closely cohesion pre and post. This station is the \( m \) process which is also the last process. Constraint (3) represents that there is a setup time interval between adjacent mould castings. Constraint (4) represents that each charge cannot be interrupted when it is processing on a station. Constraint (5) represents the constraints of the equipment. The same equipment can only process the next charge when the last one is over. Constraint (6) represents the constraints of the work order. The same charge can only continue the next station when the last one is over. Constraint (7) represents the starting time of the station. The working process’s time is remaining unchanged to half-charge having finished or in process. Constraint (8) represents that the half-charge must be produced before the deadline when it has a deadline of mould planning.

B. Mixed Whole-charge Planning and Scheduling Model of Continuous and Mould Casting.

We take the method of optimizing the time and path of the whole-charge at the same time to deal with the mixed planning and scheduling of continuous and mould casting. We select one charge \( i \in W_{j} \) every time. And then we get the next working station’s sequence number \( j \) and machine number \( k \) through rule’s iteration. Using the same method we can get the processing starting time \( X_{ijk} \) of the next work station. Also using the previous section’s notations we build the mathematical model of the mixed planning and scheduling of continuous and mould casting.

\[
\min Z = \sum_{n=1}^{N} \sum_{i=1}^{n} C_{1n} \left( X_{sl(i,m,k),m,g(i,m,k)k} - X_{i,m,k} - pt_{i,m,k} \right)
\]

\[
+ \sum_{j=1}^{m-1} \sum_{i \in \Omega} C_{2i} \left( X_{i,j+1,k} - X_{ijk} - pt_{ijk} - ut_{j,i+1}^{f} \right) \tag{9}
\]

Subject to:

\[
X_{sl(i,j,k),k} - X_{ijk} \geq pt_{ijk}, \tag{10}
\]

\[
i, sl(i,j,k) \in \Omega, j=1, \ldots, m_{j}, j \in \Theta_{sl(i,j,k)}
\]

\[
X_{i,j+1,k} - X_{ijk} \geq pt_{ijk} + ut_{j,i+1}^{f}, \tag{11}
\]

\[
j=1, \ldots, m_{j}-1, j+1 \in \Theta_{i}
\]

\[
X_{sl(i,m,k),m,g(i,m,k)k} - X_{i,m,k} \geq pt_{ijk} + adjt_{cast} \tag{12}
\]

\[
i \in \Omega, sl(i,j,k) \in \Omega_{g}, m_{g(i,m,k),k} \in \Theta_{sl(i,m,k)}
\]

\[
X_{ijk} \geq 0, i \in \Omega, j \in \Theta_{i} \tag{13}
\]

\[
st_{i,m,k} \geq T_{n}, i \in R^{*} \cap W_{0} \tag{14}
\]

The same equipment can only process the next charge when the last one is over. The same charge can only continue the next
station when the last one is over. Constraint (12) represents that there is a setup time interval between adjacent continuous castings. Constraint (13) represents that the decision variables is nonnegative. Constraint (14) represents that the whole-charge must be produced before the deadline when it has a deadline of mould planning.

5. SOLUTION METHODOLOGY

5.1 Establishing the Optimization Rules

Establish the priority constraints of mixed charging plan of continuous and mould casting:

Rule 1: if \( \delta_{(i,j,k)} = 0 \), \( i \in \Omega \) and \( \delta_{(i',j,k)} < 0 \), then charge \( i \) has the high-priority over charge \( i' \).

Rule 2: if \( \delta_{(i,j,k)} = 0 \), \( i \in \Omega \) and \( \delta_{(i',j,k)} < 0 \), then charge \( i' \) has the high-priority over charge \( i \).

Rule 3: if \( \delta_{(i,j,k)} = 0 \), \( i \in \Omega \) and \( \delta_{(i',j,k)} < 0 \), then there is no priority constraint that satisfying scheduling.

Rule 4: if \( \delta_{(i,j,k)} = 0 \), \( i \in \Omega \) and \( \delta_{(i',j,k)} < 0 \), then they have the same priority.

Rule 5: if \( \delta_{(i,j,k)} = 0 \), \( i \in R^* \), \( j \in R^* \), and \( \delta_{(i',j,k)} < 0 \), then charge \( i \) has the high-priority over charge \( i' \).

Rule 6: if \( \delta_{(i,j,k)} = 0 \), \( i \in R^* \), \( j \in R^* \), and \( \delta_{(i',j,k)} < 0 \), then charge \( i' \) has the high-priority over charge \( i \).

Rule 7: if \( \delta_{(i,j,k)} = 0 \), \( i \in R^* \), \( j \in R^* \), and \( \delta_{(i',j,k)} < 0 \), then there is no priority constraint that satisfying scheduling.

Rule 8: if \( \delta_{(i,j,k)} = 0 \), \( i \in R^* \), \( j \in R^* \), and \( \delta_{(i',j,k)} < 0 \), then they have the same priority.

When they have the same priority, the choice to this couple of charges is based on the flexible influence on scheduling sequence. The evaluation method of flexible of scheduling sequence is as follow:

\[
\phi((i,j,k),(i',j,k)) = \frac{1}{\min(\delta_{(i,j,k)}, \delta_{(i',j,k)}) + \max(\delta_{(i,j,k)}, \delta_{(i',j,k)})}
\]

(15)

5.2 The Solve Method of Half-charge Mixed Plan Based on Locked Path

The steps of half-charge mixed plan scheduling is as follows:

Step1: Get the continuous casting muster of half-charge \( H_1 \), muster of deadline mould casting plan \( H_2 \) and muster of no-deadline mould casting plan \( H_2 \). Then we get the descending sort plans according to the start time of furnace.

Step2: Select the last charge from \( W_1 \), according to the delivery time between equipments. In order to maintain the stability of production, we get the next stage’s start time according to the time of this stage’s \( e_{ij} \) and the time to former same cast production equipment \( ut_{j_1+1}(k,k') \).

Step3: Calculate \( \delta_{(i,j,k)} = 0 \), \( i \in \Omega \), \( j \in \Omega \), and \( \delta_{(i',j,k)} = 0 \), \( i \in \Omega \), \( j \in \Omega \), of the charges that come from the same equipment which are adjacent.

Step4: Check the decisional limiting condition, and do the sequencing decision to the rest of the charges.

If one of the sequencing decisions meet the rule 1 to 4, then use step 4.1-4.7 to deal with.

Step4.1: Get the continuous casting muster of half-charge \( H_1 \), and then we get the descending sort plans according to the start time of furnace.

Step4.2: Select the earliest charge in terms of starting time from \( H_1 \), according to the delivery time between equipments. Because of half-charge plan, we go ahead path lock. So only according this stage’s time of \( e_{ij} \) and \( ut_{j_1+1}(k,k') \), we get next stage’s starting time.

Step4.3: Calculate \( \delta_{(i,j,k)} = 0 \), \( i \in \Omega \), \( j \in \Omega \), \( k \in \Omega \), \( l \in \Omega \), and \( \delta_{(i',j,k)} = 0 \), \( i \in \Omega \), \( j \in \Omega \), \( k \in \Omega \), \( l \in \Omega \), of the charges that come from the same equipment which are adjacent.

Step4.4: Check the decisional limiting condition, and do the sequencing decision to the rest of the charges. If one of the sequencing decisions meets the condition 1 or condition 4, we conform the charge’s processing starting time in this stage according to constraint. Then jump to step 4.5; if one of the sequencing decisions meets the conditions 1, condition 2 or condition 3, then we jump to step 4.7.

Step4.5: Add a new charge, and then jump to step 4.1;

Step4.6: Contrapose the unsorted every couple of border upon charges calculates \( \phi((i,j,k),(i',j,k)) \). Select the smallest charge and to arrange it’s time. If \( \delta_{(i,j,k)} = 0 \), \( i \in \Omega \), \( j \in \Omega \), \( k \in \Omega \), \( l \in \Omega \), \( \delta_{(i,j,k)} = 0 \), \( i \in \Omega \), \( j \in \Omega \), \( k \in \Omega \), \( l \in \Omega \), then charge \( i \) will be processed prior to charge \( i' \) on equipment \( k \) working station \( j \), otherwise behind \( i' \) jump to step 4.5;

Step4.7: If none sequencing decision meets the rule 4, then we seek a solution to get the half-charge plan of the continuous cast, stop. Otherwise jump to step 4.6;
If one of the sequencing decision meets the rule 5 or 6, we confirm the charge’s processing starting time in this stage according to constraint, and then jump to step5; if one of the sequencing decision meets the rule 7, then we look back upon; if none sequencing decision meets the rule 1 to 8, then jump to step 7.

Step5: Add a new charge, and then jump to step1;

Step6: Contrapose the unsorted every couple of border upon charges calculates the \( \phi \left( \left( i, j, k \right) \left( i', j, k \right) \right) \).

Select the smallest charge and to arrange it's time and equipment. If \( \delta_{(i,j,k)}(i',j,k) \geq \delta_{(i',j,k)}(i,j,k) \) then charge \( i \) will be processed prior to charge \( i' \) on equipment \( k \) working station \( j \), otherwise behind \( i' \) ; jump to step5;

Step7: If none sequencing decision meets the condition 8, then we seek a solution to get the half-charge plan of the continuous and mould casting, stop. Otherwise jump to step 6;

6. NUMERICAL RESULTS

There is a mixed continuous/mould casting schedule (20 continuous casting plans, 1 deadline mould casting plan and 2 no-deadline mould casting plans). Show the result by Fig.2 of Gant is using state of half charge. Fig.3 is the result of continuous cast and mould casting plan.

Fig. 2. Using state of half charge

Fig. 3. The result of continuous and mould casting mixed plan

7. CONCLUSIONS

In this research, deep research on the scheduling and scheduling methods for the mixed production of the continuous casting and mold casting is made. The main content of this paper is as following:

1. According to the flow of actual product process, the scheduling policy is described. On base of analyzing the processes’ complexity, the steelmaking continuous and mould casting’s policy is summed up;
2. We proposed the heuristic scheduling policy of steelmaking continuous and mould casting in this paper to solve the difficult problem;
3. Tested by the actual data, it is verified that the scheduling method and policy of the steelmaking continuous and mould casting are efficient.

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