Two-stage Optimized Scheduling Method and Application for Steelmaking and Continuous Casting

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Abstract— Steelmaking and continuous casting is a difficult process that is manually scheduled due to its overwhelming number of objectives and restriction factors. This paper provides a new method of two-stage optimized scheduling for steelmaking and continuous casting. In the first stage, a preliminary schedule is established based on the same usage rate of parallel machines and minimized time conflict. In the second stage, a linear programming model of elimination time conflict is established. By solving the two mathematical models, an operable schedule is produced. The method of two-stage optimized scheduling has been embedded a scheduling system which is also developed and successfully applied to a large steel plant in China. The industrial application has demonstrated that the proposed method cannot only meet the requirement of practical production, but also has a wide application in industry.

I. INTRODUCTION

The steelmaking and continuous casting (SCC) production process belongs to hybrid flow shop (HFS). Hybrid Flow Shop Scheduling (HFSS) is a difficult NP problem [1]. There are generally two methods that deal with HFSS problems, namely the classical optimization method and the intelligent optimization method. The classical optimization methods include linear programming, integer programming, dynamic programming, branch and bound method and Lagrangian Relaxation, etc. The intelligent optimization method uses expert system, neural network and genetic algorithm etc.

Since the linear programming was first applied to the cost accounting of steel production by Fabian [2], classical optimization approach has been applied to solve the scheduling problem in the 1950s, and this approach was further developed in 1960s [3-5]. From the late 1960s, intensive study of complicated scheduling theory has been carried out. The rule-based heuristic algorithm became the main method to solve scheduling problems [6-9], and it was further improved in the 1970s [10]. In the 1980s, artificial intelligence became the mainstream of solving scheduling problems. In the late1980s, large international iron and steel factories began to utilize computer and artificial intelligence technology to develop the production control system. For example, IBM cooperated with Japan’s Kokan Iron and Steel Factory and developed the cooperative scheduling system, which is called Schplan [11]. Korean Gwangyang iron and steel factory developed the process adjusting and scheduling system, HIPASS[12]. These systems can automatically collected important data, optimize each process’s time and routing, and form production schedule, thus ensuring the rationalization and integration of production management. In the 1990s, computational intelligence was adopted in the scheduling theory. Modified genetic algorithm was used to study the sequencing problem of flow shop.[13] Yu Hai-bin [14] used neural network to study SCC scheduling problems, and proposed to solve job-shop scheduling problems with restricts of starting and completing time. In this approach, each constraint was described by a restricted neural network, accordingly adjusted the starting time unqualified with restricts, leading to a feasible scheduling plan.

The scheduling methods have been continually developed with the further study for production scheduling. Currently, the question of how many of these scheduling methods can be adopted in practical production process was raised in [15]. From the end of 20th century, the efficient scheduling methods have been studied that could be applied to practical production processes, where these methods have been embedded into the scheduling system to reduce the waiting time, the production cost and increase the competition[16, 17]. In the paper [18, 19], SCC schedule was abstracted as a 3-step HFS problem, and the scheduling mathematical model was established and solved by Lagrangian Relaxation and B&B algorithm [20], Tang Li-xin [21] established SCC scheduling model based on “just-in-time” principle, and converted it to a linear programming model according to the real meaning of variables. Then the standard linear programming software package was used to solve the model, and applied to the production of Shanghai Baosteel.
Since all computational intelligent methods need to be
given an initial solution, such methods can hardly be applied
to practical production processes. This is because different
initial solution would produce different solution speed and
the result, which would influence the stability of the system.
Most papers still use classical optimization methods to solve
practical scheduling problems. Paper [22] had established
intelligent scheduling system (ISS) according to large steel
enterprise’s need for the scheduling software, where the
architecture and function of the system were introduced in the
paper.

This paper is organized in the following way. The first
section summarizes the relevant research for hybrid flow
shop scheduling method. In Section 2, the SCC scheduling
problem and scheduling strategy of intelligent scheduling
system are described. In section 3, a two-stage optimized
schedule method is given, and finally an application example
is presented in this paper.

II. DESCRIPTION OF SCHEDULING PROBLEM

A. SCC Production Process

SCC Production Process is illustrated in Fig.1. First, raw
materials such as iron ore and dolomite are put into the blast
furnace (BF) and melted, and the liquid iron as the output
from BF is transported to the steelmaking shop where
converters are located. Converters refine liquid iron into
molten steel. The melted steel is poured into ladles that are
transported by crane and trolley to a refining furnace. Special
treatment may be performed in the Ladle-refining equipment
to eliminate impurities from either molten steel or add alloy
ingredients to the molten steel to make high-grads steel.
Finally, casters cast molten steel continuously into billets, and
the billets are rolled into steel products needed by customers.

B. Complexity of SCC Production Process

During the entire iron and steel production process, the
products are being processed and handled at high temperature
with physical and chemical reactions. The production process
is a hybrid process, which has both characteristics of
continual and the discrete phases. The production scheduling
of continual processing phase is relatively easy due to its line
flow, but the discrete processing phase is a multi-stage,
multi-equipment, parallel, asynchronous process. Thus, the
selection of multi-equipment paths is a key during the process
(proven to be the NP-hard problem). Similar to discrete
processing phase, SCC also needs to select among
multi-equipment paths since the production process involves
multiple converters, refining furnaces and continuous casters.
The quality of steel bloom is closely related with the
temperature and ingredient of molten steel arriving at caster,
therefore long wait time between operations is not allowed.
Otherwise, the molten steel has to be reheated which causes
high energy consumption and low quality of steel bloom. As a
result, it is extremely important to control the flow time of
charges. The molten steel must be delivered to caster on time
with prearranged ingredient standard and ideal temperature.
Therefore, production scheduling in hybrid type phase has
been recognized as one of the most difficult industrial
scheduling problems.
C. Scheduling Strategy

In order to solve the problems mentioned above, an intelligent scheduling system (ISS) had been developed [22]. The proposed scheduling strategy of SCC production process is illustrated in Fig.2. Firstly, according to the cast planning, optimized goals and constraints, two schedules are generated by expert system and optimization model method separately. The better scheme is selected by evaluation criteria established by the manufacturing process. When schedule cannot be carried out properly due to the incident disturbing, the schedule is adjusted by case-based reasoning (CBR) approach.

1) Optimization Method

SCC production schedule can be described as: based on the given cast plan M, each cast contains N charges, assign these N charges to several stations of the J processes, under the condition of correct joint and casting continuously on the same cast, determine the job schedule of each machine, and minimize the objective function (the total flow time, waiting time between processes).

From the definition of SCC production schedule, it can be seen that there are two questions needed to be resolved:

1. Machine selected:
Because each process contains not only one machine, this requires to determine the charges’ converter furnace first, refining furnace second, and continuous caster last. This means that it needs to select an optimal production path for the charges. Suppose that one charge needs to pass three production processes (converter furnace, refining furnace and continuous caster), each process contains three identical machines, so there are $M_1 \times N$ production paths as shown in Fig.3. This is an optimization problem to choose which path, which is needed to be resolved.

2. Conflict Elimination:
When selecting the production path of the charges, with the given condition (charges’ job order and starting casting time in continuous caster, the processing time on each machine, and the transportation time between machines), we can backward infer the charges’ starting time and completing time corresponding to the machine in the process of continuous caster, refining furnace and converter furnace, and produce the job schedule of charges. However, the two charges (i and q) in different continuous caster may be assigned to the same refining machine (LF furnace), and after backward inferring to the refining machine (LF furnace) according to the starting casting time of each continuous caster, the conflict problem between job time will happen. As such, this is not a feasible scheduling plan. We need to eliminate this conflict, and produce a schedule that there are not job time conflicts on any machines.

2) Expert System

The scheduling expert system consists of a knowledge base, a reasoning machine, a database, the man-machine interface, a knowledge gained part and an interpreter. A great lot facts and the rules that can be used to solve scheduling problems are stored in the knowledge base. The function of reasoning machine is to select facts and rules related to user’s problem from knowledge base and carry out reasoning according to the certain strategy. Expert system interacts with users through the man-machine interface. On one hand it accepts user's information and translates them into the internal form which the system can process. On the other hand the useful knowledge generated by reasoning machine from the knowledge base are sent back to users. The interpreter is that the scheduling results and proposed problems in scheduling process are explained rationally by using knowledge from the knowledge base and facts from the database. The working principle of expert system is the charge plan etc, so that information is sent to the reasoning machine by man-machine interface and the inference machine according to scheduling. Then the reasoning machine searches mutuality knowledge from the knowledge base and each fact from the database and carries out matching and the reasoning. Finally, the reasoning results (namely the scheduling result) are returned to the users through the man-machine interface.

3) Evaluation

![Fig.2 Scheduling Strategy SCC Production Process](image)

![Fig.3 Workflow of steelmaking and continuous casting process](image)
Because there are two different schedules in the static scheduling subsystem in terms of how excellent scheme can be selected in actual production, it is necessary that reasonable evaluation scheme is set up. The three evaluation indices are established in system. (1) The total charges waiting time is minimized for the concerned equipment; (2) the variance of equipment load is minimized; (3) the waiting time variance of the charge on the equipment is minimized. 

The evaluation functions of three indexes are established, the better schedule is selected by the fuzzy evaluation method and the simulation effect. This schedule will be sent to SCC production process by the scheduling instructions.

4) Case-Based Reasoning 
Case-Based Reasoning (CBR) is a scheme with which production incidents can be solved and then stored in the case-memory, where the schedulers can retrieve and reuse them to solve similar case in SCC production process at any time. SCC production process is complex and shop floor events are various. To speed up the adjustment, we classified the previous cases into seven categories such as equipment, ingredient, and temperature and so on. When shop floor event occur, the category of the event is determined. Category descriptors and current status information are input into computer by scheduler, then the scheme of similar case may be found in case memory accordingly, Adjustment for new problem is generated either by the scheme found in case memory or by adapting an original scheme. If the scheme of similar case has not been found in case memory, an adjustment has to be given by scheduler. Every adjustment is sent to the Gantt simulation editor. If the scheduler satisfies the simulating result of the scheme and then the adjustment is sent to SCC production spot. Otherwise the scheme must be modified and sent to the Gantt simulation editor again until the result is satisfactory. The successful scheme is stored in the case memory for future use.

III. TWO-STAGE SCHEDULING METHOD

The scheduling process is divided into two-stages. In the first stage, a mathematical model of machine assignment is developed, and the charges are assigned to machines heuristically to produce a preliminary time table. In the second stage, other mathematical model of conflict management is developed and solved by standard linear programming, with the goal of minimizing cost and ensuring punctual start of casting.

A. The Mathematical Model of Machine Assignment

1) Notations

\( T_{ijk} \) \( \) the processing time of plan \( i \) on machine \( k \) of process \( j \);

\( x_{ijk} \) \( \) the starting processing time of plan \( i \) on machine \( k \) of process \( j \);

\( \Omega_{jk} \) \( \) the set of all charges on machine \( k \) of process \( j \);

\( \Pi_{qj} \) \( \) the set of all machines used for process \( j \) in plan \( q \);

\( f_q(i, j, k) \) \( \) the time conflict function of charge \( i \) and \( q \) on machine \( k \) of process \( j \);

\( E_q(i, j, k) \) \( \) the set of all charges \( i \) conflicting with charge \( q \) on machine \( k \) of process \( j \);

\( F_q(i, j, k) \) \( \) the minimum of all charges \( i \) conflicting with charge \( q \) on machine \( k* \) of process \( j \);

\( G(j, k) \) \( \) the load function on machine \( k \) of process \( j \);

2) Machine Assignment Model

(a) Machine conflicts function

Assume that \( T_{ijk} \approx T_{qjk} \), then we can obtain

\[
F_q(i, j, k) = \sum_{j \in \Omega_{jk}} f_q(i, j, k)
\]

where

\[
f_q(i, j, k) = \begin{cases} 
T_{qjk} & \text{if } |x_{qjk} - x_{ijk}| \leq T_{ijk} \\
0 & \text{else}
\end{cases}
\]

(b) Machine load function

\[
G(j, k) = \sum_{i \in \Pi_{qj}} T_{ijk}
\]

3) Steps of Solution

(a) Basic assumption

The following assumption must be considered before the schedule is constructed.

- The sequences of charges are fixed on casters.
- The charges casting continuously on the same caster are considered as a cast.
- There is one cast joining scheduling in each caster at most.
- Assuming that the starting casting time in each caster, the processing time on machines, and the transportation time between machines were given.

(b) Steps of solution

Step1: From the starting casting time, select the refining machine according to the refining mode of charges, compute the conflict function on available refining machines, and determine the machine with the least conflicts by comparison.

\[
F_q(i, j, k*) = \min_{k \in \Omega_{jk}} F_q(i, j, k)
\]

Step2: When the least conflict time of two or more available machines is the same, compute the load value of available machines and find the machine with the least load value.

\[
G(j, k) = \min_{k \in \Omega_{jk}} \sum_{i \in \Pi_{qj}} T_{ijk}
\]

Step3: When the least load value of two or more machines is the same, choose the machine with the minimal number. 

A preliminary schedule can thus be obtained after above steps. Since usually there will have time conflicts on some machines, we also need to eliminate these conflicts in order to make this preliminary schedule feasible.

B. The Mathematical Model of Machine Conflicts Eliminated

1) Notations

\( n \) \( \) cast serial number;

\( N \) \( \) cast number \( n=1,2, \ldots, N \);
i  serial number of charge;
j  serial number of process;
m  serial number of machine;
Ωn  the set of all charges in the nth cast;
Ωn0  the set of the first charge in the nth cast;
S  the set of process;
Si  the set of the ith charge pass process
Scc  the set of all casters
Mj  the set of all machines in jth process;
C1  coefficient of cast break lost penalty for cast k;
C2  coefficient of penalty cost for the waiting time of charge i after finishing process on machine j;
C3  coefficient of penalty cost for the first charge in the kth cast starting casting after the time specified;
C4  coefficient of penalty cost for the first charge in the kth cast starting casting after the time specified;
\(T_{r}^{i, j, m} \)  processing time from machine m to machine m' in j process;
\(T_{p}^{i, j} \)  time parameters are presented table II. As the complicated production flow in China, the system has three converters; seven refining furnaces which including three RHs, two CASs, one KIP and one LF and three continuous casters.
Jn  starting time of charge i on the machine m of jth process;
\(X_{i, j, m}^{k} \)  starting time of charge i' that the immediate charge i processed on same process j and machine m;

2) Production constraints
• For the two contiguous operations for the same charge, only when the preceding operation has been completed the next one can be started.
• For two contiguous charges processed on the same machine, only when the preceding charge has been completed, then the next one can be started.

3) Optimized objective
It is important that the following are achieved.
• Wait time is as short as possible form operation to operation.
• Cast break loss penalty is minimum.
• Loss penalty that the first charge in each cast cannot be cast on time is minimum.

4) Decision variable
Use the starting processing time of charge i on machine k of process j as the decision variable of conflict elimination linear programming model, and note as \(X_{i, j, m}^{k} \), then the optimized objective function is as follows:

\[
\min Z = \sum_{n=1}^{N} \sum_{i \in \Omega_n, j \in S, m \in M_j} C_i (X_{i, j, m} - X_{i, j, m}^{k}) + \sum_{n=1}^{N} \sum_{i \in \Omega_n, j \in S, m \in M_{j+1}} C_{i,j} (X_{i, j, m} - X_{i, j, m}^{k}) + \sum_{n=1}^{N} (C_3 Y_{i, m} + C_4 Z_{i, m})
\]

A. Introduction of the NO. 1 steelmaking factory
The No. 1 steelmaking factory is a branch of Shanghai Baoshan Iron and Steelmaking Corporation (Baosteel in short) that is the largest iron and steel enterprise in China. Baosteel started to use digital machines and computer systems in a large scale from the beginning of 1970’s when it was founded. In the middle of 1980’s, when the second construction began, the basic automatic control system (L1); process control system (L2); production control computer system (L3); enterprise management system (L4) were imported. However, in the No. 1 steelmaking factory, the schedule making and adjusting is still done manually which is not suited for the realization of CIMS in the factory. Therefore during the third construction phase, a strategy has been proposed, which is to embed a model of steelmaking and continuous casting in the L3 system so as to replace the manual adjustment. Therefore we developed the intelligent scheduling system on the requests of Baosteel.

The NO.1 steelmaking factory has majority machines with the twelve charges to be processed. The initial parameters for these jobs are given in table I. The route of charges assigned based on the assignment scheduling model in first phase and time parameters are presented table II. As the complicated production flow in China, the system has three converters; seven refining flow which including three RHs, two CASs, one KIP and one LF and three continuous casters.
B. An Example

Fig.4 shows a screen shot of three casts plan table on 12/10/2005. There are twenty charges need to be arranged, including seven charges in No.1 caster, six charges in No.2 caster and seven charges in No.3 caster.

Fig.5 shows a screen shot of the schedule generated by the two-stage optimized scheduling method based on the plan (Fig.4), the horizontal axis represent time; the vertical axis represent the equipment; the thick line stand for the process time of each charge on each equipment; the thin diagonal line represent transportation time of the charge form machine to the next machine; the vertical broken line is current time of computer, and the charges cast on same caster is represented by same color.

C. Application Effect

The application result has indicated that: (1) the time of constructing a schedule has been significantly decreased; a schedule with 20 charges is constructed in 30 seconds by the ISS. (2) the times of on-the-spot adjustment has been reduced. The number of average adjustment per day reduces to 1/10; the hit probability of time, ingredient and temperature (are called three hit probability) from original 54% has been enhanced to 65.7%. (3) Daily charges have been increased from 53 to 58, and daily production has been increased by 7%.

V. CONCLUSION

Whether steelmaking, refining and continuous casting can be well coordinated in production is an important criteria to evaluate the production and management level of an iron and steel enterprise. SCC production scheduling is one of the core technologies in coordinating steelmaking, refining and continuous casting, and receives much attention from large steel factories. As a result, it is important to develop an effective scheduling system to minimize the waste of manpower and resources. In this paper we have established a novel two-stage mathematical model which is suitable for general steel factories scheduling plan. This model is verified by the production data and the scheduling simulation platform of a large steel factory. The result shows that this scheduling method can be successfully applied in the industry.

VI. REFERENCES