Research Approaches on Integrated Planning for Iron and Steel Enterprises

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Abstract—With the development of production technologies in iron and steel enterprises, integrated production technology comes into use for steelmaking and continuous casting as well as hot rolling. It is important to establish an integrated production planning and scheduling system to improve the productivity. In this paper, based on integrated management, planning models including steelmaking, continuous casting and rolling are presented. The planning models serve as the basis for the establishment of a charge-slabs-rolling unit batch planning model which finally leads to an integrated scheduling. The solution of the integrated scheduling is introduced in the end.

Key words: Charge, Cast, Rolling, Integrated batch planning, Integrated scheduling

I. INTRODUCTION

FOR energy saving, newly emerged production technologies, such as hot-charging rolling, direct-charge rolling, direct-rolling, etc. make it possible for the three working procedures (steel making, continuous casting, continuous rolling) to be closely linked in primary steelmaking area, and to turn the iron and steel production into an integrated system [1-2]. The improvement of the technologies gives rise to higher demand for production management, especially for the establishment of an integrated scheduling system. Reasonable production planning and scheduling method can improve productivity, shorten waiting time of working procedures, and lower the consumption of material and energy. Thus, the cost is decreased and production competitive abilities enhanced. Many large iron and steel enterprises have begun to devote to the development of the integrated scheduling of steelmaking-continuous casting-hot rolling (SR) since 1980s. Therefore, it is possible for the transformation from local optimization to global optimization.

Unlike general production scheduling in machine industry, iron and steel production scheduling problems have to meet special requirements of steel production process. There are extremely strict requirements on material continuity and flow time, e.g. processing time on various devices, transportation and waiting time between operations. Many iron and steel scheduling problems have been studied through typical mathematical modeling, such as travel salesmen problem (TSP), Bin-packing problem, Shortest-path, Knapsack problem, and have been proved to be NP-hard. Presently, many researches are being focused on the modeling of steelmaking-continuous casting (SCC) and hot rolling (HR). Solving operational management problems for SCC and HR production has been widely reported. In SCC scheduling aspect, Lally et al. [3] established a simple mixed-integer linear programming solution to the problem of casting scheduling. They considered a simple model of a steel plant in which steel was started at an electronic 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. Tong et al. [4] constructed a complex mixed-integer linear programming model, and solved it using heuristic techniques for twin strand continuous slab caster scheduling problem at LTV and Geneva Steel Workers. LTV caster scheduling model was implemented in support of the first continuous caster installed at LTV Cleveland Workers in 1983. The model was intended to schedule caster production from customer order while optimizing several key objectives such as maximizing caster productivity. Neuwirth [5] reported a linear programming model with machine conflicts and provided key modeling factors of SCC scheduling and charge allocation scheme in the furnace, but the mathematical representation of the model was not given. Lixin Tang et al. [6] developed a mathematical programming model, with the JIT idea, to solve machines conflicts in SCC production scheduling in the CIMS environment, and gave the mathematical representation of the model. In HR scheduling aspect, Redwine and Wismer [7] proposed an off-line iron and steel production and scheduling model based on the mathematical programming and found solution to the problem through dynamic programming algorithm. Balas and Martin [8] reduced the hot rolling production scheduling problems to the knapsack constraint problems and prize collecting TSP models. For a single roll scheduling, they designed the Roll-A-Round program. Xiong Chen et al. [9] put forward a mathematical model to HR scheduling problem of vehicle...
routing with time window to describe the rolling lot planning, and solved it using genetic algorithm (GA). Kosiba et al.\cite{[10]} investigated the hot strip sequencing problem and established a TSP model. Lixin Tang et al.\cite{[11]} proposed a multiple traveling salesmen problem (MTSP) for rolling scheduling using the parallel strategy, and solved it with GA too. However, this model only solved the single roll scheduling problem. Up to now, to our understanding, the researches on mathematical programming model for SR in literature have been rarely reported. On the basis of SCC and HR production planning and with the combination of SCC and HR planning, a charge-slab-rolling unit batch planning model is established. Thus, the comprehensive research on SR scheduling is made from integrated aspect.

This paper is organized as follows. Section 2 introduces SR production background. In section 3, SCC and HR models are described. Based on the SCC and HR models, a Charge-Slabs-Rolling unit batch Planning model is established in section 4. Section 5 introduces the SR integrated production scheduling system structure. The solution method of Lagrangian relaxation (LR) is introduced to solve the SR model in section 6. Finally, conclusions are drawn in section 7.

II. BACKGROUND

There are three major manufacturing processes: steelmaking, continuous casting and rolling in primary steelmaking. The steelmaking process starts with the liquid iron tapped from BF (Blast Furnace), and crude steel transported to the steelmaking shop where CF (Converter Furnace) and/or EAF (Electric Arc Furnaces) are located. CF and EAF burn out the excessive carbon, sulfur, silicon, and other impurities from liquid iron and refine it to steel with desired contents. Here, the filling of one furnace is called a charge. Charge is a unit of production that consists of a sequence of operations on a heat. The refined steel already contains the main alloying elements. In the RF (Refining Furnace), special treatment is performed to eliminate impurities from molten steel or add alloy ingredients to the molten steel to make high-grade steel. In succession, the CC (Continuous Caster) casts molten steel continuously into slabs, blooms, or billets. Cast is a set of charges that continually casts on the same continuous caster and has a similar chemical composition. The continuous casting plate blanks or rough rolling plate blanks are rolled into order blanks and refined using rough rolling mill, then cooled, rolled up and polished. Because of the high temperature, high speed and heavy wear, work rollers and backup rollers on each stand need replacing to ensure the shape of plates and orders need remaining flat. Rolling objects between two work rollers are called a rolling unit. The SR production process is illustrated in Fig.1.

The continuous casting-continuous rolling (CCR) is a novel production manner developed from the integration of newest technologies of SR. The development of CCR production dramatically promotes the revolution in technology and management, and at the same time, raises higher level demand to the production management technologies, especially to planning and scheduling. The CCR production can be categorized into the following kinds and illustrated in Fig.2 where CC-HCR denotes Continuous casting-Hot Charge Rolling, CC-DHCR denotes Continuous casting-Direct Hot Charge Rolling, CC-DR denotes Continuous casting- Direct Rolling, and CC-CCR denotes Continuous casting-Cold Charge Rolling.

In the production of CCR, especially in CC-DHCR and CC-DR, direct connection of three big working procedures, steelmaking, casting, rolling, is realized. Facing this highly integrated continuous productive system, traditional management schemes are no long practicable. Novel management, namely computer based integrated production management, must be taken.

![Fig.1. The SR production process](image-url)
III. MODEL DESCRIPTION

The Steelmaking, continuous casting, and hot rolling procedure in iron and steel enterprises are well known as three big working procedures among which exits not only the balance of material flow and resource, but also that of time. In conditions of market economy, solving the problem of integrated production scheduling should start with the customers’ contracts, and establish the manufacturing plan which satisfy the customers’ demand and the constraints in the working procedures. In traditional iron and steel production, three big working procedures are independent of each other, and the interaction among them is very slight. Production plans are established and conducted individually. Moreover, there are a batch of semi-manufactured goods in the working procedures used as middle inventory. From the above statements, it can be seen that traditional production management is applicable only to a certain working procedure, with little consideration to the up and/or down working procedures, so that it only achieves local or partial optimization for a single segment or working procedure.

A. SCC Model Description

Generally speaking, the connection between SCC mainly concerns how to raise the amount of charges in the casts. Most modern iron and steel enterprises put steelmaking procedure and continuous casting procedure together into the same production area. This action is lucrative whether to process control or to the production scheduling. The continuous casting procedure is strictly concerned with ingredient, temperature and arrival time of molten steel. How to coordinate the procedures to minimize the conflicts of equipments and the temperature loss of molten steel between steelmaking and continuous is the main goal in SCC scheduling. SCC production scheduling problems are to determine in what sequence, at what time and on which device molten steel should be arranged at various production stages from steelmaking to continuous casting.

The SCC production scheduling is time-table planning of charges based on batch planning. The model for the optimal scheduling problem is formulated as follows:

\[
\text{Min } Z_{SCC} \tag{1}
\]

The objective function \(Z_{SCC}\) for this model is to ensure continuity of the production process. This is achieved through minimizing a cost function consisting of the following terms:\(a\) Casting break loss penalties exerted to ensure that charges in the same caster are casting continuously as possible, \(b\) Molten steel temperature drop cost in terms of waiting time from operation to operation.

The constraints are considered in the model to guarantee that there will be no machine conflicts in the schedule generated. The constraints include two contiguous operations for the same charge, two contiguous charge processed on the same machine, setup time and interval required from cast to cast on the same caster.

B. HR Model Description

Generally, Hot Rolling working procedure concerns how to increase the number of slabs in the rolling units. Hot rolling puts forward strict demand on temperature, width, gauge and hardness and arrival time of continuous casting slabs. Mainly, there are three considerations in the hot rolling scheduling: \(1\) production quality; \(2\) roller replacement cost; \(3\) roller wear. The cost of the roller replacement is so great that it is necessary to organize as many orders as possible within the range of maximal rolling length constraint of a turn to reduce the replacement cost. The rolling sequence affects the roller wear. In order to guarantee
production quality, the staple material rolling section should meet the following requirements: the total length (or weight) of the staple materials is limited to a given quantity; each staple order is no wider than the one that precedes it and the width jump should be small; width, gauge and hardness jumps are not permitted to occur simultaneously; order gauge which is not allowed to jump repeatedly should change smoothly; hardness should change gently, gradually increasing or decreasing. When changes in hardness, gauge and width compete against each other, the order of priority is: hardness, gauge and then width. How to coordinate the procedures to minimize the conflicts of equipments and the temperature loss of slabs between continuous casters and hot rollers is the main goal in hot rolling scheduling.

The HR production scheduling is time-table planning of slabs based on batch planning. The model for the optimal scheduling problem is formulated as follows:

\[ \text{Min } Z_{HR} \]

The objective function \( Z_{HR} \) for this model is to ensure continuity of the production process and JIT delivery of final products. This is achieved through minimizing a cost function consisting of the following terms: (a) Rolling break loss penalties exerted to ensure that slabs in the same rolling unit are rolling as continuously as possible. (b) Slabs temperature drop cost in terms of waiting time from operation to operation. (c) Earliness/tardiness penalty used to ensure that each slab is delivered as punctually as possible.

The constraints are considered in the model to guarantee that there will be no machine conflicts in the schedule generated. The constraints include two contiguous operations for the same slab, two contiguous slabs processed on the same machine, setup time and interval required from rolling unit to unit on the same roller.

IV. INTEGRATED BATCH PLANNING MODEL

The production of continuous casting and continuous rolling, especially the mode of CC-DHCR or CC-DR, realizes direct connection among smelting, casting and rolling, which makes SR integrated. Here, the basic unit of SR planning and scheduling is combined batch which is made up of charge, cast and slab. The batch combination planning problem which integrates multi-procedures is limited by two-stage constraint (SCC and HR). The main constraint of SCC batch planning (charge and cast) is steel scale and specifications, with steel scale to be the same, and specifications to be close. The main constraint of HR batch planning model is width and gauge, with width required to change gently and gradually decreasing and gauge to change smoothly. The two constraints above should be taken into account in the integrated batch planning. Thus, the three-stage constraints including steelmaking, continuous casting and hot rolling have to be analyzed systematically in the research on SR integrated batch planning problem.

There is not only connection but also difference between integrated batch planning and traditional batch planning. The integrated batch planning will enhance the complexity of the problem. In SCC scheduling model, charge is the minimal job. However, in the HR scheduling model, slab is the minimal job. The relation of rolling unit, charge and slab is presented in Fig.3.

The model for the optimal Charge-Slabs-Rolling unit batch planning is formulated as follows:

\[ \text{min } \sum_{i=1}^{N} \sum_{k=1}^{R} (P_{ik}^W + P_{ik}^G + P_{ik}^H) \]

subject to

\[ \sum_{k=1}^{R} X_{ik} \leq D, l = 1,2,\ldots,L \]

\[ \sum_{i=1}^{N} X_{ik} = 1, l = 1,2,\ldots,L \]

\[ \sum_{i=1}^{L} X_{ik} = 1, i = 1,2,\ldots,R \]

Where \( P_{ik}^W \), \( P_{ik}^G \), \( P_{ik}^H \) representing the width, gauge and hardness penalties from slab \( i \) to successive slab of the \( kth \) charge in the \( lth \) rolling unit. \( D \) is the capacity constraint

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of the rolling unit. \( R \) is the sum of slabs, \( N \) is the sum of charges, and \( L \) is the sum of the rolling units.

\[
X_{ikl} = \begin{cases} 
1, & \text{if the } i \text{th slab in the } k \text{th charge} \text{ is assigned in the } l \text{th rolling unit;} \\
0, & \text{otherwise} 
\end{cases}
\]

The objective function (3) for this model is to minimize the sum of jumps in the width, gauge and hardness penalties. Constraint (4) for the capacity of the rolling unit : Constraint (5) and (6) representing the slab can be rolled once in the roller.

V. SR INTEGRATED SCHEDULING MODEL

A. SR Integrated scheduling System Structure

SR integrated scheduling puts forward extremely strict requirements on material continuity and flow time with SR generally belonging to no waiting procedure. With regard to CC-DHCR or CC-DR production mode, on the basis of integrated batch planning (charge, cast and rolling unit) and with charge (or slab) as the minimal unit, the essence of SR integrated scheduling is to seek the optimal objective of special multi-job, multi-procedure and multi-machine Job Shop. That is, the essence of SR integrated scheduling is to determine in what sequence, at what time and on which device the job should be arranged at various production stages from steelmaking to hot rolling. SR integrated scheduling, on the basis of batch planning of charge, cast and rolling unit, arranges sequence and schedule on charge and rolling unit respectively, and eliminate machine conflicts by making use of the optimal model. Integrated batch combination (charge-slab-rolling unit) is made by the connection among charge, slab and rolling unit, thus forming SR integrated scheduling. Figure 4 shows SR integrated scheduling system structure.

B. SR integrated scheduling model

The SR production scheduling is time-table planning of slabs based on integrated batch planning (Charge – Slabs – Rolling unit batch planning). The model for the optimal scheduling problem is formulated as follows:

\[
\min Z_{SR} \\
Z_{SR} = Z_{SCC} + Z_{HR}
\]

The objective function \( Z_{SR} \) for this model is to ensure continuity of the production process and JIT delivery of final products. The constraints include the constraints of both \( Z_{SCC} \) and \( Z_{HR} \).

VI. SOLUTION

A. LR for SR Integrated Model

The iron and steel production planning is a large-scale combination optimal problem, which is proven to be NP-hard problem. It is hard to get a satisfying solution in effective time. Lagrangian relaxation (LR) technology has been proven to be very effective in the solving of the complex scheduling problem\(^{12-13}\). Lixin Tang et al. make use of LR in SCC mathematical programming model to get solution\(^{16}\). They utilize the decomposition of LR to transform the complex large-scale non-linear programming problem into a series of sub-problems. The dynamic programming is used to get the solution to each sub-problem. A satisfying solution is achieved in the end. Based on this idea, the SR production scheduling model is solved by LR technology\(^{17}\). The steps are shown as following:

Step1): Relax the original problem by LR multipliers, and set up the duality problem;

Step2): Decompose the original problem to get different sub-problems (decomposed as charge or slab sub- problems), and solve each sub-problem by dynamic programming;

Step3): Solve the dual problem, and modify LR multipliers by sub-gradient method;

Step4): Construct a feasible schedule by list- scheduling procedure, for some constraints can be violated within certain scope;

Step5): Evaluate the feasible solution via the approximate duality gap.

B. An Example

Fig.5 presents an example of the SR integrated production scheduling. In this example there are two converter furnaces (CF), two refining furnaces (RF), two continuous casters (CC) and two continuous rollers (CR). SR integrated production scheduling model considers eight charges, four rolling units and forty slabs. Basic model parameters are given in Tab.1. The processing time of slabs are given at random.

First, the SCC and HR production model were solved by using common programming methods (linear and dynamical programming) respectively. \( Z_{SCC} = 307 \), \( Z_{HR} = 261 \).
Fig.5. SR Process Routes

The simulation is carried out on PIII 800, visual C++6.0 by using LR. All the multipliers were initialized to zero. The lower bound is obtained 440, and the feasible schedule has a cost $Z_{SR} = 499$ with a relative duality gap of 13.2%.

VII. CONCLUSION

In the traditional iron and steel plants, steelmaking, continuous casting and rolling are independent of each other, and the production plans are designed and conducted separately, so that only local or partial optimization can be obtained. Based on the SCC and HR scheduling models, an integrated production scheduling model was put forward in the research. Complying with practical cases, the integrated model considered the problems in production technology and working procedures, such as continuous manufacturing, just-in-time delivery of orders, etc. With regard to SR integrated scheduling, a charge-slab-rolling unit integrated batch planning model is established. SR integrated production scheduling is finally formed on the basis of the integrated batch planning. The solution method of SR integrated schedule is introduced, and numerical examples were given to demonstrate the effectiveness of the integrated model and optimization methods in the end.

REFERENCES