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# Simultaneously scheduling multiple turns for steel color-coating production

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ABSTRACT

This paper investigates a large-scale scheduling problem in the iron and steel industry, called *color-coating production scheduling* (*CCPS*). The problem is to generate multiple production turns for the galvanized coils that dynamically arrive from upstream lines within a given scheduling horizon, and at the same time determine the sequence of these turns so that the productivity and product quality are maximized while the production cost and the number of generated turns are minimized. We formulate this problem as a mixed integer nonlinear program and propose a tabu search heuristic to obtain satisfactory solutions. Results on real production instances show that the presented model and heuristic are more effective and efficient with comparison to manual scheduling. A practical scheduling system for *CCPS* combining the model and heuristic has been developed and successfully implemented in a major iron and steel enterprise in China.



## 1. Introduction

Generally speaking, the operations in an integrated steel plant can be classified into two sections: primary steel production operations and finishing operations (Fig. 1). In the primary steel production, raw materials such as iron ore and coal are transformed sequentially into liquid iron in a blast furnace, into liquid steel in a steel making furnace, into large solid steel slabs in a continuous caster, and into hot steel coils in a hot strip mill (HSM). Various finishing operations are then applied to the semi-finished products from the primary steel production process to obtain final products according to customers' specifications. For coils requiring color-coating, the finishing process starts from pickling that removes oxidation on surfaces. Then the coils are rolled into thin coils in the cold mill (CM) and go through a continuous annealing line (CAL) followed by an electro-galvanizing line (EGL) or alternatively through a continuous galvanizing line (CGL). The galvanized coils are released to the coil yard in front of the color-coating line and then finished with a color-coating process according to their required coat colors.

Solving production planning and scheduling problems in the iron and steel industry is an important research topic and has been widely explored recently. As reviewed by Tang et al. [1], most research on scheduling and systems for integrated steel production is focused on the primary operations, especially the hot rolling production.

A primary production scheduling problem including continuous caster and hot strip mill (HSM) was studied by Lee et al. [2], in which two methods were proposed for caster scheduling and a third method was proposed for integrated caster and HSM scheduling respectively. Balas and Martin [3] studied the hot rolling production scheduling problem and presented a prize collecting traveling salesman problem (PCTSP) model. Kosiba et al. [4] investigated the hot strip sequencing problem and established a traveling salesman problem (TSP) model. Lopez et al. [5] formulated the hot strip mill production scheduling problem as a generalization of the PCTSP, and proposed a tabu search heuristic to obtain good solutions. This TSP and PCTSP modeling, much like manual planning, only considers one turn at a time. A turn is the continuous processing of slabs between two working roller replacements. Working rollers should be replaced after a certain number of slabs have been rolled to maintain rolled coil quality. The scheduling objects of these kinds of models are only the slabs that have arrived at the slab yard, and after a turn is generated by selecting the best available slabs from the slab yard, the slabs in it are fixed and are not considered in the generation of the following turns. The final production schedule which consists of a set of turns sequenced according to their generation sequence may still be further improved, i.e. by exchanging slabs between two turns. Therefore, these kinds of models may result in poor long-term performance due to their greedy and myopic nature.

To avoid the disadvantage of the TSP and PCTSP models, researchers turn to investigate parallel modeling strategies that can simultaneously generate multiple turns for slabs stored in the slab yard. Based on the parallel modeling strategy, Tang et al. [6] presented a multi-

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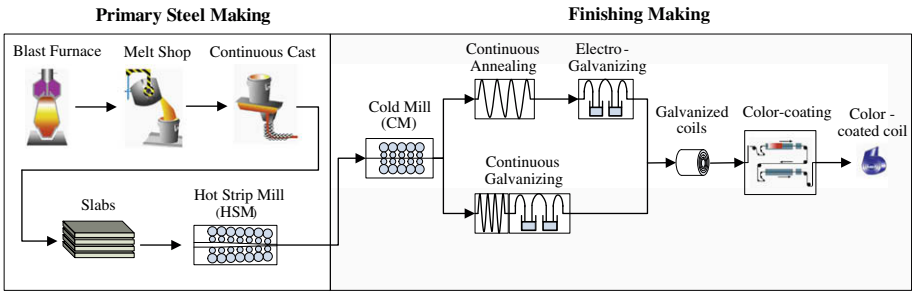


**Fig. 1.** Primary and finishing operations in iron and steel enterprises.

ple traveling salesman problem (MTSP) model and a genetic algorithm for the hot rolling production scheduling problem, and Cowling [7] proposed a prize-collecting vehicle routing problem (PCVRP) model and a tabu search heuristic for a hot rolling mill. However, the MTSP and PCVRP models just determine which slabs to group in each turn and how these slabs are sequenced in each turn. They do not take into account the production sequence between generated turns. To be implemented in practical production, the production sequence of these turns must be determined at the same time. Because the time window limitations of practical production (such as the due date) are not taken into account in these models, the sequencing of generated turns may often result in infeasible schedules or a great tardiness penalty.

Little published research focuses on scheduling problems for finishing operations. Wang et al. [8] presented a genetic algorithm based optimization procedure for the scheduling of tandem cold rolling mills. Okano et al. [9] described the finishing line scheduling problem in a major steel mill in Japan, which is to assign coils to turns for four continuous lines (CM, CGL, CAL, EGL) and to sequence coils in each turn so that productivity and product quality are maximized while tardiness of coils is minimized.

All of the above papers deal in some way with a scheduling problem in the steel industry, most focusing on primary production and few on finishing production. However, to the best of our knowledge, there has been no study in the literature that addresses the *color-coating production scheduling* (*CCPS*) problem. Therefore, in this paper we focus our attention on the color-coating process, which transforms the galvanized coils into color-coated coils. Like the requirement in HSM, to ensure product quality, the coating rollers should be replaced after processing a certain weight of coils, which is called the *capacity* of the color-coating production line, and the continuous processing of coils between two coating roller replacements is also called a turn. *CCPS* is to generate multiple turns for the galvanized coils that dynamically arrive from upstream production lines within a given scheduling horizon, and at the same time determine the sequence of these turns so that the productivity and product quality are maximized while the production cost and the number of generated turns are minimized.

In most iron and steel enterprises, the *CCPS* is commonly conducted by skilled human experts. However, various constraints along the production flow and timeline with respect to the sequence of turns and the sequence of coils in each turn often make it very difficult for them to generate satisfactory schedules with low production cost and tardiness penalty. To avoid the disadvantages suffered by the previous researches on the hot rolling scheduling problem, we formulate the *CCPS* problem as a mixed integer nonlinear programming model using a monolithic modeling strategy that can simultaneously generate multiple turns and at the same time determine the sequence of these turns, and develop a tabu search heuristic leading to satisfactory results on real production instances. A practical scheduling system for *CCPS*, combining the mathematical model and the tabu search heuristic with a man-machine interactive method, has been developed and successfully implemented in Shanghai Baoshan Iron and Steel Co. Ltd. (*Baosteel*).

The rest of this paper is organized as follows. The color-coating production process and the scheduling constraints are described in Section 2. Section 3 establishes the mixed integer nonlinear programming model for the *CCPS*. The tabu search heuristic applied to the *CCPS* is then presented in Section 4. Section 5 reports the computational results on real production instances. At last, the paper is concluded in Section 6.

## 2. Color-coating production process and scheduling constraints

### 2.1. Production process

Fig. 2 illustrates the main process flow of the color-coating production line. Because this line operates in a continuous way, the galvanized coils are first opened to steel plates on the unwinding machine. Immediately following the unwinding machine is a welding machine that welds the end of a plate to the start of the next. Then the welded plates continuously go through the later processes in the following order: pre-treatment, primer coating on both sides, finishing coating on both sides, surface post-treatment to improve the integration of steel plate and the color coats, shearing, and rewinding the coils again.

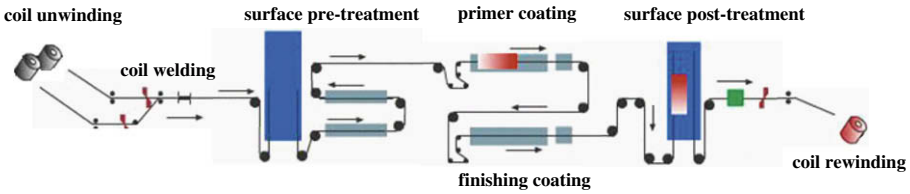


**Fig. 2.** Main process flow of the color-coating production.