Simultaneously scheduling multiple turns for steel color-coating production

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A B S T R A C T
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-
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.](image-url)
Fig. 3a shows the construction of a color-coating turn, with each bar representing a coil. Because a coil generally has two layer coats on both sides, we use the down-half of the coil in the figure to show the primer coat color while the up-half to show the finishing coat color. As shown in Fig. 3b, whenever the primer or finishing coat colors between two adjacent coils $i$ and $j$ in a turn are different, a transition coil must be inserted between them during production so that there is enough time to clean out the paint required by coil $i$ from the rollers and to dip the new paint required by coil $j$ on the rollers while the production continues. Such a color change between two adjacent coils in a turn is called a color switch, which will inevitably cause time and paint waste. Because the coating rollers do not work while a transition coil is processed, the weights of the transition coils need not be included in the turn capacity. Because the time needed for the changeover of the color coats on coating rollers is generally a fixed value, transition coils can be assumed to have the same processing time in practical production.

### 2.2. Color-coating scheduling constraints

There are four main considerations in color-coating scheduling: (1) productivity; (2) product quality; (3) cumulative tardiness time of orders; and (4) order integrity. In practical production scheduling, schedulers often consider productivity to be more important than product quality, which is more important than tardiness of orders and order integrity.

Productivity means gross production per week or month excluding coils that cannot be delivered because of flaws or scars. In practical production, there are mainly four factors that can affect productivity. The first one is the time gap between turns that includes a fixed work roller setup time and an unfixed time interval from the ready time of new work rollers to the start time of next turn (Fig. 4). A big time gap between turns allows more candidate coils to arrive before the next turn starts and thus may improve the quality of the turn, it is required that this time gap should not exceed a certain value $T_{\text{max\_gap}}$ so as to improve productivity. The second time gap is between adjacent coils in a turn. If coil $i$ is scheduled to be completed in time $t_1$ but the earliest start time of its following adjacent coil $j$ is $t_2$ ($t_1 < t_2$), then a time gap between them occurs (Fig. 4). To keep the production continuity, the start of this turn must be delayed or transition coils must be inserted into this time gap. Because transition coils cannot be sold as product, this kind of time gap leads to lower productivity. Therefore, it is required that the time gap between adjacent coils should not exceed a certain value $T_{\text{max\_gap}}$. The third time gap is for color switches and dramatic width or thickness changes between adjacent coils. It is preferred that the coils with the same color be adjacent in a turn and the changes of width and thickness be smooth so that as few transition coils as possible are used during production. The fourth time gap is the replacement of bearing rollers in an unwinding machine or the replacement of embossing rollers in the post-treatment process due to the changeover in inner diameter or embossing type of adjacent coils. It is better for coils with the same inner diameter and embossing type to be adjacent in a turn so as to reduce the number of replacements of both bearing rollers and the embossing rollers. Among these factors, the color switch is usually considered as the most important one by human schedulers.
To guarantee product quality, the width of adjacent welded coils must strictly transit from wide to narrow; otherwise color scars are left on the following coil, which causes coils unable to be delivered as a finished product. When a galvanized coil has been released to the coil yard, it should be scheduled and processed within a certain time. Otherwise an extra pre-treatment procedure must be applied on it before it is coated, which increases the production cost. We define freshness of a coil as the time left when the coil leaves the coil yard with respect to the maximum permitted inventory time (Fig. 5). It is clear that the fresher the coils are, the smaller the production and inventory cost will be.

Minimization of the cumulative tardiness time of orders means that as many products as possible should be delivered before their due dates.

During practical production, all candidate coils have been assigned to some customer orders. An order can be delivered on its due date only if all the coils belonging to it have been processed, so the earlier processed coils of an order have to be stored at the finished coil yard if the coils belonging to this order are arranged in several parts of a turn, which causes additional inventory cost. Therefore, it is preferable for coils belonging to the same order to be arranged adjacently in a turn. Such a requirement is called order integrity.

3. Mixed integer nonlinear programming (MINLP) model for CCPS

3.1. Parameters and variables

Because the penalties (or costs) for changes in width and thickness, for changeovers of bearing rollers and embossing type, and for color switches are totally dependent on the physical properties of two adjacent coils, the penalties from coil to coil can be obtained by direct computation of a penalty structure that reflects the conditions in the color-coating line. We only use the changeover penalty of orders between two adjacent coils to approximately act as the penalty for the violation of order integrity so as to reduce the computation efforts. There is a difference between a case where an order that has few coils (with short processing time) inserted between two adjacent coils of the same order and a case where there are many coils (requiring substantial processing time) inserted between the same two adjacent coils. However, the difference generally has little influence on the objective function value because the violation of order integrity has the least importance. As costs resulting from time parameters, the penalties for time gaps, low freshness of coils, and tardiness of coils can also be obtained from a coil sequence. Therefore the CCPS problem becomes to generate multiple production turns and at the same time determine the sequence of these turns so as to minimize the total penalties. To establish the mixed integer nonlinear programming (MINLP) model for the CCPS problem, the following symbols are used for parameters and variables.

**Parameters:**

- $N$ the set of coils, $N = \{0, 1, 2, \ldots, n\}$, where 0 denotes a dummy coil
- $W$ the set of penalty coefficients, $W = \{w_1, \ldots, w_{12}\}$
- $Q$ the capacity of a turn
- $G$ the fixed cost to activate a new turn
- $H$ the maximum permitted inventory time for each coil
- $r_i$ the release time of coil $i$
- $d_i$ the due date of coil $i$
- $b_i$ the width of coil $i$
- $g_i$ the thickness of coil $i$
- $q_i$ the weight of coil $i$
- $p_i$ the processing time of coil $i$ on the color-coating line
- $d_{1ij}$ The color switch penalty of adjacent coils $i$ and $j$, which includes the penalty for the time spent on transition coil and the penalty for waste of coat materials. Let $P_{top}$, $P_{btm}$, $P_{top}$, and $P_{btm}$ denote the color switch time of the primer top, the primer bottom, the finish top and the finish bottom respectively. And let $M_{top}$, $M_{btm}$, $M_{top}$, and $M_{btm}$ denote the coat material loss of the primer top, the primer bottom, the finishing top and the finishing bottom respectively. Then the time penalty and the coat material waste penalty can be defined as follows.

1. **primer top time penalty** $r_{1ij}^t = \begin{cases} 0 & \text{if } i, j \text{ have same primer top color;} \\ w_1 P_{top} & \text{otherwise} \end{cases}$
2. **primer bottom time penalty** $r_{1ij}^b = \begin{cases} 0 & \text{if } i, j \text{ have same primer bottom color;} \\ w_1 P_{btm} & \text{otherwise} \end{cases}$
3. **finishing top time penalty** $r_{1ij}^f = \begin{cases} 0 & \text{if } i, j \text{ have same finishing top color;} \\ w_1 P_{top} & \text{otherwise} \end{cases}$
4. **finishing bottom time penalty** $r_{1ij}^m = \begin{cases} 0 & \text{if } i, j \text{ have same finishing bottom color;} \\ w_1 P_{btm} & \text{otherwise} \end{cases}$
5. **primer top loss penalty** $m_{1ij}^p = \begin{cases} 0 & \text{if } i, j \text{ have same primer top color;} \\ w_2 M_{top} & \text{otherwise} \end{cases}$
6. **primer bottom loss penalty** $m_{1ij}^b = \begin{cases} 0 & \text{if } i, j \text{ have same primer bottom color;} \\ w_2 M_{btm} & \text{otherwise} \end{cases}$
(6) primer bottom loss penalty \( m_{ij}^7 = \begin{cases} 0, & \text{if } i, j \text{ have same primer bottom color;} \\ w_2 M_{bfin}' & \text{otherwise} \end{cases} \)

(7) finishing top loss penalty \( m_{ij}^8 = \begin{cases} 0, & \text{if } i, j \text{ have same finishing top color;} \\ w_2 M_{fstop}' & \text{otherwise} \end{cases} \)

(8) finishing bottom loss penalty \( m_{ij}^9 = \begin{cases} 0, & \text{if } i, j \text{ have same finishing bottom color;} \\ w_2 M_{bfin}' & \text{otherwise} \end{cases} \)

Because the changeovers of primer and finishing color coats on rollers are performed simultaneously, we have

\[
d_{ij} = \max (t_{1,i}^1, t_{1,j}^1, t_{1,j}^2) + (m_{ij}^1 + m_{ij}^2 + m_{ij}^4).
\]

\(d_{2y}\) The penalty for the change of width and thickness of adjacent coils \(i\) and \(j\). Let \(\sigma_1\) and \(\sigma_2\) be the maximum permitted change for width and thickness of adjacent coils respectively. Since at most one transition coil is permitted to be inserted for dramatic changes, the penalty for width change of adjacent coils \(i\) and \(j\) can be computed by

\[
d_{2y}^1(i,j) = \begin{cases} w_5 (b_i - b_j), & \text{if } 0 \leq b_i - b_j \leq \sigma_1 \\
(1 - a)w_4, & \text{if } \sigma_1 < b_i - b_j \leq 2\sigma_1, \infty, \text{otherwise} \end{cases}
\]

and the penalty for the thickness change can be computed by

\[
d_{2y}^2(i,j) = \begin{cases} w_5 |g_i - g_j|, & \text{if } |g_i - g_j| \leq \sigma_2 \\
(1 - a)w_4, & \text{if } \sigma_2 < |g_i - g_j| \leq 2\sigma_2, \infty, \text{otherwise} \end{cases}
\]

\(a = \begin{cases} 0, & \text{if coils } i \text{ and } j \text{ have the same colors} \\
1, & \text{otherwise} \end{cases} \). The parameter \(a\) is introduced to handle the situation where two adjacent coils have simultaneously different coat colors and violation of change limitation in width or thickness. Then we have

\[
d_{2y} = \max(d_{2y}^1, d_{2y}^2).
\]

\(d_{3y}\) The penalty for the order integrity of adjacent coils \(i\) and \(j\).

\[
d_{3y} = \begin{cases} 0, & \text{if } i, j \text{ belong to the same order} \\
\infty, & \text{otherwise} \end{cases}
\]

\(d_{4y}\) The penalty for the embossing type changeover of adjacent coils \(i\) and \(j\).

\[
d_{4y} = \begin{cases} 0, & \text{if coils } i, j \text{ have same embossing types} \\
\infty, & \text{otherwise} \end{cases}
\]

\(d_{5y}\) The penalty for the bearing roller changeover of adjacent coils \(i\) and \(j\).

\[
d_{5y} = \begin{cases} 0, & \text{if coils } i, j \text{ have same inner diameter} \\
\infty, & \text{otherwise} \end{cases}
\]

\(d_y\) The distance between coils \(i\) and \(j\), which is the sum of \(d_{1y}, d_{2y}, d_{3y}, d_{4y},\) and \(d_{5y}\). We set \(d_0 = 0\) and \(d_0 = 0\) for all \(i \in N\).

**Integer variables:**

\( m \) The number of generated turns \(m = |V|\) where \(V\) denotes the set of generated turns.

\[
x_{ik} = \begin{cases} 1, & \text{if coil } j \text{ is processed directly after coil } i \text{ in turn } k (i \neq j); \\
0, & \text{otherwise} \end{cases}, \quad i, j \in N, k \in V.
\]

\[
y_{ik} = \begin{cases} 1, & \text{if coil } i \text{ is selected to be processed in turn } k; \\
0, & \text{otherwise} \end{cases}, \quad i \in N, k \in V.
\]

\[
z_{kl} = \begin{cases} 1, & \text{if turn } l \text{ is processed directly after turn } k (k \neq l); \\
0, & \text{otherwise} \end{cases}, \quad k, l \in V.
\]

**Continuous variables:**

\(B_i\) The start time for production of turn \(k\).

\(C_i\) The completion time for production of turn \(k\).

\(c_i\) The completion time of coil \(i\), which is determined by the processing time of coils and transition coils arranged before coil \(i\) in the schedule, plus the time gaps between adjacent turns.

\(D_i\) The penalty for the delivery tardiness of coil \(i\), \(D_i = w_9 \times \max\{c_i - d_i, 0\}\).

\(F_i\) The penalty related to the freshness of coil \(i\), \(F_i = w_{10} \times \max\{c_i - p_i - r_i - H\}\).

\(T_{IA}\) The penalty for the time gap between adjacent turns, \(T_{IA} = w_{11} (B_i - C_i) z_{ik}\).

\(t_{ij}\) The penalty for the time gap between adjacent coils, \(t_{ij} = w_{12} \times \max\{(r_j - c_i)/p', 0\}\), where \(p'\) is the average processing time of transition coils.

3.2. Mathematical model for the CCPS

To differentiate the importance of the penalty items, we use six preset constants \(\hat{a}_i \in [0, 1], i = 1, 2, \ldots, 6\) and \(\sum_{i=1}^{6} \hat{a}_i = 1\). Using the parameters and variables described above, the CCPS problem can be formulated as a MINLP model below.
A tabu search heuristic for the CCPS

3.3. Characteristics of the CCPS

Due to the special features of the CCPS, algorithms proposed for the vehicle routing problem with time windows cannot be applied directly to it. To the best of our knowledge, there exist no algorithms directly applicable to the CCPS either. Considering that tabu search (TS) heuristics have been successfully applied to solve combinatorial optimization problems in the iron and steel industry ([5,7]), we also de-

Based on the MINLP model presented above, the CCPS has the following characteristics compared to the hot rolling production scheduling: (1) sequence-dependent color switches: different sequence of adjacent coils in a turn results in different color switches, and thus different costs of material loss; (2) sequence-dependent time gaps: the time gaps between adjacent turns and the time gaps between adjacent coils in a turn are greatly affected by their sequence; (3) soft time windows: each coil has a release time, a maximum permitted inventory time and a due date, but these time windows are not strict since coils can be delayed for processing and delivery with penalties.

When a turn is viewed as a vehicle and a coil as a customer, the mathematical model for CCPS can be considered as an extension of the VRPTW, and consequently it is also strongly NP-hard.

4. A tabu search heuristic for the CCPS

Due to the special features of the CCPS, algorithms proposed for the vehicle routing problem with time windows cannot be applied directly to it. To the best of our knowledge, there exist no algorithms directly applicable to the CCPS either. Considering that tabu search (TS) heuristics have been successfully applied to solve combinatorial optimization problems in the iron and steel industry ([5,7]), we also de-

Each item in the objective function (1) represents one type of cost. The first is the total penalties for color switches, jumps of width and gauge, order integrity, and changeovers of bearing rollers and embossing type. The second and third are the penalties for delivery tardiness and freshness of all coils respectively. The fourth is the setup cost of all active turns. The fifth and sixth are the penalties for time gaps between adjacent turns and between adjacent coils in a turn. Constraints (2) ensure that each coil can only be color coated exactly once. Constraint (3) ensures that the number of generated turns is m, which is a decision variable. Constraints (4) are the typical flow conservation equation that ensures production continuity. Constraints (5) ensure that each turn starts from and ends at the dummy coil. Constraints (6) are the capacity constraint of each turn. Constraints (7) and (8) ensure that the turns are processed sequentially and that the time gap between adjacent turns cannot exceed a certain value. Constraints (9) ensure that the first coil arranged in each turn; note that M is a very large number. Constraints (11) ensure that the coils are processed from wide to narrow. Constraints (12) and (13) ensure that the coils are processed sequentially and that the time gap between adjacent coils cannot exceed a certain value. Constraints (14)–(17) specify the integrity and nonnegative conditions respectively on the decision variables.

3.3. Characteristics of the CCPS

Minimize \[ \sum_{k \in V} \sum_{i \in N} d_{ik} x_{ijk} + \lambda_2 \sum_{k \in V} \sum_{i \in N} D_{ik} y_{ik} + \lambda_3 \sum_{k \in V} \sum_{i \in N} F_k y_{ik} \]

\[ + \lambda_4 M g + \lambda_5 \sum_{k \in V} \sum_{i \in N} t_{ik} x_{ijk} \]

s.t. \[ \sum_{i \in N} y_{ik} = 1, \quad \forall i \in N \setminus \{0\} \]

\[ \sum_{i \in N} y_{ik} = m \]

\[ \sum_{i \in N} x_{ijk} = \sum_{i \in N} x_{ijk} = y_{ik}, \quad \forall k \in V, \quad \forall i \in N \]

\[ \sum_{i \in N} x_{ijk} = \sum_{i \in N} x_{ijk} = 1, \quad \forall k \in V \]

\[ \sum_{i \in N} y_{ik} q_i \leq Q, \quad \forall k \in V \]

\[ B_k + p_i - (1 - x_{ijk}) M \leq c_i, \quad \forall i \in N \setminus \{0\}, \quad \forall k \in V \]

\[ x_{ijk} = 0, \quad \text{if } b_i > b_i \text{ for } \forall i, j \in N \setminus \{0\}, \quad \forall k \in V \]

\[ y_{ij} \in \{0, 1\}, \quad \forall i, j \in N \setminus \{0\}, \quad \forall k \in V \]

\[ B_k + p_i - (1 - x_{ijk}) M \leq c_i, \quad \forall i \in N \setminus \{0\}, \quad \forall k \in V \]

\[ x_{ijk} \in \{0, 1\}, \quad \forall i, j \in N \setminus \{0\}, \quad \forall k \in V \]

\[ y_{ik} \in \{0, 1\}, \quad \forall i \in N \setminus \{0\}, \quad \forall k \in V \]

\[ q_i \in \{0, 1\}, \quad \forall k \in V, \quad \forall k \in V \]

\[ z_{ij} \in \{0, 1\}, \quad \forall k \in V, \quad \forall k \in V \]
velop a TS heuristic for the CCPS problem following the general guidelines proposed by Glover [15,16]. To accelerate the local search procedure, two kinds of speedup strategies are developed based on the characteristics of the CCPS problem.

4.1. The initial solution

The proposed constructive heuristic to obtain initial solutions is essentially a greedy algorithm based on the simple mechanism of the cheapest-insertion heuristic (CIH). When implementing the CIH, we incorporate the practical production constraints and the time gaps as a factor in the coil selection criterion. To delete the time gaps between coils in a turn, traditional manual methods just insert transition coils. However, this method may suffer from the disadvantage of more color switches when the time gap exists between two coils that have the same color or the disadvantage of more production time when the time gap is very small with comparison to the average processing time of a transition coil. Therefore, we propose a new method that combines the insertion of transition coils and the delay of the start time of a turn (Fig. 6).

To describe the constructive heuristic, we define the following symbols. Let \( t_{\text{end}} \) be the completion time of the coil arranged at the end position of the turn being scheduled, and \( Q_k \) the sum of weight of coils arranged in turn \( k \). Let \( P \) be the set of candidate coils that have arrived at the coil yard at the time \( t_{\text{end}} + \frac{t_{\text{gap}}}{C_0} \), and \( V_{pk} \) the subset of \( P \) with coils that can be inserted into turn \( k \). Let \( L_k \) denote the cumulative delay time of the start time of turn \( k \), and \( \Delta t \) a fixed time interval. Then the constructive heuristic for the initial solution of CCPS problem can be described as follows.

**Step 1.** Set \( t_{\text{end}} = 0 \), \( L_k = 0 \), \( Q_k = 0 \), and the set of coils \( N = \{1, 2, \ldots, n\} \).

**Step 2.** Update the candidate coil set \( P \). If \( P = \Phi \), go to Step 4; otherwise, go to Step 3.

**Step 3.** Update \( V_{pk} \). If \( V_{pk} = \Phi \), go to Step 5; otherwise, select from \( V_{pk} \) the coil with the minimum increased value of the objective function and insert it into turn \( k \) at the best position. Then update \( t_{\text{end}} \) and \( Q_k \), delete this coil from \( N \), and go to Step 2.

**Step 4.** If \( N = \Phi \), stop because all coils have been scheduled; otherwise, go to Step 5.

**Step 5.** If no capacity is left for any coil to be inserted, go to Step 9; otherwise, go to Step 6 if \( P = \Phi \) while go to Step 7 if \( N \neq \Phi \) and \( V_{pk} = \Phi \).

**Step 6.** Find the earliest arrival time of coils in \( N \), \( e = \min_{i \in N} \{e_i\} \). If \( L_k + (e - t_{\text{end}}) \leq t_{\text{gap}} \), delay the start time of turn \( k \) and set \( L_k = L_k + (e - t_{\text{end}}) \), \( B_k = B_k + (e - t_{\text{end}}) \), \( t_{\text{end}} = t_{\text{end}} + (e - t_{\text{end}}) \), then go to Step 2; otherwise, go to Step 8.

**Step 7.** If \( L_k + \Delta t \leq t_{\text{gap}} \), set \( L_k = L_k + \Delta t \), \( B_k = B_k + \Delta t \), \( t_{\text{end}} = t_{\text{end}} + \Delta t \), and then go to Step 2; otherwise, go to Step 8.

**Step 8.** If there is enough remaining capacity in turn \( k \) (for example \( Q_k/Q \leq 0.8 \)), insert a transition coil at the end of the turn \( k \), set \( t_{\text{end}} = t_{\text{end}} + p' \) (\( p' \) is the processing time of the inserted transition coil), and then go to Step 2; otherwise, go to Step 9.

**Step 9.** Set \( k = k + 1 \), \( L_k = 0 \), \( Q_k = 0 \), \( t_{\text{end}} = t_{\text{end}} + T_g \), and then go to Step 2.

Since there are always a certain number of coils stored in the coil yard to ensure the safe inventory in practical production, a feasible solution can always be found using this greedy constructive method.

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**Fig. 6.** Methods of deleting the time gaps between adjacent coils in a turn.
4.2. Parameters used in the TS heuristic

**Neighborhood:** The neighborhoods of our TS heuristic are based on three edge-swapping moves: (1) **relocate:** delete a coil from a turn and insert this coil into another turn (Fig. 7); (2) **exchange:** exchange two coils between different turns (Fig. 8); and (3) **swap:** swap two coils in a turn. Among the three moves, the relocate and exchange moves are used to generate neighborhoods for local searches in the TS, while the swap move is only used to further improve the local optima obtained by local searches.

**Tabu list:** Each element in the tabu list is the complete description of a move including the relative turns and the move. When carrying out the experiment, we found that it is better to set the size of the tabu list to 10 in our heuristic.

**Stop criteria:** The search process terminates when one of the following two common stopping criteria is satisfied: (1) the maximum number of iterations (100) has been reached; (2) the maximum number of continuous iterations (40) without improvement on the value of the objective function has been reached.

4.3. Speedups for the TS heuristic

To accelerate the local search, we propose two kinds of **speedup** strategies. The first evaluates a move before it is performed and based on the evaluation the feasibility checking of time gaps in the new solution generated by this move can be accelerated. The second combines certain coils that have the same properties as one coil to reduce the problem size.

4.3.1. Speedup strategy 1

For the relocate move shown in Fig. 7, let \( \Delta_1 \) be the decreased time between \( c_{\text{prev}_i} \) and \( c_{\text{next}_j} \), and \( \Delta_2 \) the increased time between \( c_j \) and \( c_{\text{next}_j} \). Then the following remark 1 can be used to accelerate the feasibility checking of the local search in the relocate neighborhood.

**Remark 1:** If \( \Delta_1 \leq \Delta_2 \), the time gaps between coils \( (i, \text{next}_j) \), coils after \( \text{next}_j \) in turn \( l \) and coils in turns arranged after \( l \) are still feasible.

For the exchange move shown in Fig. 8, assume that coils \( i \) and \( j \) are arranged in turn \( k \) and turn \( l \) respectively and that turn \( k \) is arranged before turn \( l \), and let \( t_{\text{gap}} \) be the maximal time gap between coils arranged after coil \( i \) in turn \( k \), coils in turns arranged after \( k \) but before \( l \), and coils before \( \text{prev}_j \) (including \( \text{prev}_j \)) in turn \( l \). Then the following remark 2 can be used to discard the exchange moves that will result in infeasible solutions.

**Remark 2:** Assume (a) \( \text{color}(i) \neq \text{color}(\text{prev}_i) \) and \( \text{color}(i) \neq \text{color}(\text{next}_j) \); (b) the exchange of coils \( i \) and \( j \) does not violate the capacity and width constraints; (c) \( \sigma_1 < b_{\text{prev}_j} - b_{\text{next}_j} \leq 2\sigma_1 \) and \( \sigma_2 < g_{\text{prev}_j} - g_{\text{next}_j} \leq 2\sigma_2 \). Then if the processing times of coils \( i \) and \( j \) cannot satisfy: \( p_i - p_j \leq t_{\text{max}} - t_{\text{gap}} - t_{\text{gap}} \), the solution obtained by this exchange move of coils \( i \) and \( j \) is infeasible.
For the swap move, it is obvious that this move can only be applied between coils that have the same width because the width of adjacent coils must transit from wide to narrow.

4.3.2. Speedup strategy 2

To present the second speedup strategy, we first give the definition of identical coils.

Definition 1. If the width, thickness, length (processing time), coat colors, inner diameter, embossing type, arrival time and due date of coils belonging to an order are the same, then such coils are called identical coils.

Based on the definition, it is clear that the identical coils have zero transition penalties between each other, and thus it will be better for the identical coils to be arranged together in turns to reduce the color switches (the most important factor that affects the production cost). Therefore, in our heuristic a series of identical coils is viewed as a whole when being moved around in the turns. In the new neighborhood structure under this strategy, some solutions that cannot be reached in the original neighborhood structure are included. Therefore this strategy allows larger-step moves while reducing the number of potential moves from each solution. Hence, it can speed up the local search. Though the application of this strategy in the local search may affect the solution quality, it can efficiently reduce the computation time, which is very important for algorithms applied in practice.

5. Computational results

5.1. Tuning the set of penalties and objective weights

Since the items in the objective function are conflicting with each other, we first consult with the skilled human experts and find a proper setting of $W = \{w_1, w_2, \ldots, w_{12}\}$ and $\lambda = \{\lambda_1, \lambda_2, \ldots, \lambda_6\}$ according to the experience of the skilled human experts and the practical production condition, so this initial setting is valid for every instance derived from practical production. Then we use the method proposed by Okano [17] to tune these parameters. Like Okano [17], we first give some notation used in the tuning procedure. Given several real-data instances $i \in I$, let $F(S(i), W, \lambda)$ be the objective value for the solution $S(i)$ with penalty $W$ and objective weight $\lambda$, and $F_j(S(i), W, \lambda)$ the $j$-th item value in the objective function of the solution $S(i)$. For simplification, we only describe the tuning procedure of the set of penalties $W$ because the set of objective weights $\lambda$ can be tuned in the same way.

Step 1. Obtain the solutions $S_i(i)$ using the manual scheduling method with $W$.
Step 2. Fix $\lambda$, and slightly change $W$ to $W’$.
Step 3. Obtain the solution $S(i)$ for all $i \in I$ using the tabu search heuristic with $W’$.
Step 4. If $F(S(i), W’, \lambda) < F(S_i(i), W, \lambda)$ and $F_j(S(i), W’, \lambda) < F_j(S_i(i), W, \lambda)$ for all $i \in I$ and $j = 1, 2, \ldots, 6$, then set $W = W’$.
Step 5. Go to Step 1 until a satisfactory set of penalties $W$ has been found.

5.2. Computational results

To demonstrate the applications of the mathematical model and the tabu search heuristic, they have been employed to generate color-coating schedules using eight instances of real production data in Baosteel. In these testing instances, the number of coils in each instance ranges from 313 to 386; each customer order generally includes 1 to 4 coils, so the number of customer orders is about 120–150 in each instance, and therefore the number of different colors in each layer of coils is also about 120–150; the width of coils ranges from 700 mm to 1350 mm; the thickness of coils ranges from 0.3 mm to 0.75 mm; the weight of coils is about 3–28 tons; the processing time of coils is about 20–40 minutes; taking the time that a schedule is to be generated as 0, the release time of coils ranges from −10 days to 20 days, and the due date of orders varies much from −10 days to 20 days.

The algorithm was programmed in C++ and run on a P4 3.0GHz computer with 512 MB RAM. The computational results of the previous manual scheduling system (denoted by Man) and our tabu search heuristic (denoted by Alg) are given in Table 1, where $n$ denotes the number of all candidate coils, $f_{\text{obj}}$ is the objective function value, $N_1$ is the number of created turns in a schedule, $N_2$ is the number of color switches per 1000 tons of coils, $f_{\text{tardiness}}$ is the total tardiness cost, $f_{\text{inventory}}$ is the total inventory cost (which is determined by the freshness of coils) and CPU is the operation time (seconds) of Alg.

<table>
<thead>
<tr>
<th>Instance (n)</th>
<th>$f_{\text{obj}}$</th>
<th>Main items of the objective function</th>
<th>$N_1$</th>
<th>$N_2$</th>
<th>$f_{\text{tardiness}}$</th>
<th>$f_{\text{inventory}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Man</td>
<td>Alg</td>
<td>CPU</td>
<td>Man</td>
<td>Alg</td>
<td>Man</td>
</tr>
<tr>
<td>1 (313)</td>
<td>1.2116</td>
<td>1.0000</td>
<td>520</td>
<td>1.0000</td>
<td>1.0000</td>
<td>1.0769</td>
</tr>
<tr>
<td>2 (325)</td>
<td>1.3316</td>
<td>1.0000</td>
<td>404</td>
<td>1.0000</td>
<td>1.0000</td>
<td>1.0870</td>
</tr>
<tr>
<td>3 (327)</td>
<td>1.0715</td>
<td>1.0000</td>
<td>543</td>
<td>1.0000</td>
<td>1.0000</td>
<td>1.1250</td>
</tr>
<tr>
<td>4 (329)</td>
<td>1.4653</td>
<td>1.0000</td>
<td>642</td>
<td>1.0000</td>
<td>1.0000</td>
<td>1.0426</td>
</tr>
<tr>
<td>5 (338)</td>
<td>1.3376</td>
<td>1.0000</td>
<td>583</td>
<td>1.0000</td>
<td>1.0000</td>
<td>1.0912</td>
</tr>
<tr>
<td>6 (359)</td>
<td>1.1623</td>
<td>1.0000</td>
<td>249</td>
<td>1.0000</td>
<td>1.0000</td>
<td>1.0943</td>
</tr>
<tr>
<td>7 (373)</td>
<td>1.5041</td>
<td>1.0000</td>
<td>568</td>
<td>1.0000</td>
<td>1.0000</td>
<td>1.0714</td>
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<td>8 (386)</td>
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<td>1517</td>
<td>1.0000</td>
<td>1.0000</td>
<td>1.1273</td>
</tr>
<tr>
<td>Average</td>
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<td>1.0000</td>
<td>628.25</td>
<td>1.0000</td>
<td>1.0000</td>
<td>1.0805</td>
</tr>
</tbody>
</table>
From the results shown in Table 1, the following observations about our tabu search heuristic can be made.

1. The proposed tabu search heuristic obtains better solutions with respect to all the factors considered, compared to the previous manual scheduling system. And the average improvement of the objective function value is about 30%.
2. When the proposed tabu search heuristic is applied, the number of color switches, the tardiness cost, and the inventory cost are all reduced greatly (about 8%, 32%, and 5% respectively).

Based on these observations, we can conclude that our heuristic achieves tremendous improvements over the previous manual approach. These improvements have many positive implications for the company such as the reduction of production cost, the improvement in productivity, the reduction of tardy delivery of coils, and the improvement in the relationships with customers.

A practical scheduling system for CCPS, combining the presented mathematical model and the TS heuristic, has been developed and successfully implemented in Baosteel. The system (Fig. 9) is considered by the schedulers a very useful tool to improve their work.

6. Conclusions

In this paper we studied the color-coating production scheduling problem in the iron and steel industry, which 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. Taking into account the practical production constraints, we built a mixed integer nonlinear programming model for this problem. To obtain satisfactory solutions, a tabu search heuristic is proposed and two kinds of speedup strategies are developed to accelerate the local search based on the characteristics of the problem. Combining the tabu search heuristic with man-machine interactive method, a scheduling system for this problem has been developed and successfully implemented in Shanghai Baoshan Iron and Steel Co., Ltd, the most advanced iron and steel enterprise in China. Computational results on instances collected from the real production data show that the developed scheduling system can obtain about 30% improvement over the previous manual scheduling system.

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