Ladle intelligent re-scheduling method in steelmaking–refining–continuous casting production process based on BP neural network working condition estimation

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Abstract
Frequent delays will be experienced in the start-up of molten steel on the converter equipment during the steelmaking–continuous casting (SCC) production process due to the untimely supply of molten iron or scrap, which may cause conflicts between adjacent heat on the same equipment or in the same casting. The casting machine is cut off, resulting in the failure of the static scheduling plan. SCC production ladle re-scheduling is based on the premise that the production process path remains unchanged, the operation of adjacent heat on the converter and refining furnace does not conflict, and the casting of adjacent heat within the same casting is continuous. The ladle re-scheduling of steelmaking and continuous casting production aims at continuously casting many charges with the same cast and avoiding conflicts of adjacent charges on the same machine. This mechanism proposes a method of ladle re-scheduling in the production process of steelmaking–refining–continuous casting, which is divided into two parts: plan re-scheduling and ladle optimisation scheduling. Firstly, a re-scheduling optimisation model of the steelmaking and continuous casting production is built. This model aims at minimising the waiting time of all charges. The re-scheduling strategy of steelmaking and continuous casting production is proposed by interval processing time of charges and scheduling expert experience. This strategy is composed of two parts: re-scheduling charge decision and charge processing machine decision. Then, the first-order rule learning is used to select the optimisation target to establish the ladle optimal scheduling model. The ladle matching rules are extracted on the basis of the rule reasoning of the minimum general generalisation. The ladle optimisation scheduling method that consists of the optimal selection of the ladle and the preparation of the optimal path of the ladle is proposed. Ladle selection is based on the production process and adopts rule-based reasoning to select decarburised ladle after choosing dephosphorised ladle. Ladle path preparation, which is a multi-priority heuristic method, is designed to decide the path of the ladle from the converter to the refining furnace to the continuous casting machine. Finally, this mechanism was actually verified based on the large-scale data of a steel company in Shanghai, China. Results showed that the production efficiency of steelmaking-refining-continuous casting was improved.

Keywords Steelmaking–continuous casting · Re-scheduling · Ladle · BP neural network · First-order rules learning · Heuristic

1 Introduction
Modern steelmaking and continuous casting production are composed of multiple converters that refine furnaces and tundishes (the container for holding molten steel; the capacity is approximately 1/3 of the capacity of the ladle), continuous casting machines and steel ladles [1, 2]. The molten steel is poured into a transfer ladle after being processed in the converter. The molten steel in the converter is called a charge. The charge of molten steel is transported using a crane to a refining furnace. The molten steel undergoes various refining processes at the refining stage. Finally, the molten steel is transported using a crane to a caster (a set of charges incessantly drained into a tundish of a continuous caster and solidifies in a crystalliser is called a cast).

This research is based on the large-scale data of a steel company in Shanghai, China. The main equipment resources for the steelmaking–continuous casting (SCC) process are shown in Fig. 1.
The steelmaking plant is the most complicated steel production process of its kind compared with Italian Steel [3], Sha Steel, Panzhihua Steel and Qianan Steel [4]: (1) smelting is divided into single smelting (the converter only has decarburisation) or double smelting (firstly dephosphorises and then decarbonises), refining (one furnace is processed on one or more refining furnaces, called single or multiple refining, respectively) including 1–4 refining (the equipment has four types, namely, RH, LF, IR-UT and CAS); (2) the ladle matching needs to consider multiple constraints; and (3) the precise transportation time needs to be determined by the ladle path and transportation equipment scheduling. The corresponding production equipment includes the converter, ladle refining furnace and continuous casting machine. The converter and continuous casting machine are fixed. The ladle refining furnace consists of two parts of equipment: one part is the ladle (mobile) that holds molten steel, and the other part is the furnace cover that heats the electrode, vacuum tank and other equipment (fixed). The transportation equipment includes cranes and trolleys. The production scheduling is an optimisation problem of integrated production batch scheduling, selection of loading equipment and transportation equipment scheduling. SCC production in a dynamic environment also has multiple disturbance characteristics.

In previous studies on SCC production systems, researchers used artificially estimated transportation time as known conditions. The selection of the heat ladle is not regarded as decision making (the ladle is a part of the ladle refining furnace, which is equivalent to the refining equipment of the processing heat that is not fully arranged), and the static scheduling problem of the production equipment is studied [5]. The field test found that: the time disturbance is more than 80%, and the production equipment cannot be accurately scheduled. The main reason is that the refining equipment for processing heat has not been fully arranged (lack of ladle options), and the transportation route has not been considered. Therefore, the ladle re-scheduling problem must be studied on the basis of the actual needs, which has an important theoretical value and practical significance.

2 Research status of SCC ladle re-scheduling

Production scheduling problems can be divided according to the type and quantity of machines: single machine scheduling problems [6], parallel machine scheduling problems [7], open shop scheduling problems [8], job shop scheduling problems [9], flow shop scheduling problems [10], mixed flow shop scheduling problems [11] and flexible Job shop scheduling problem [12]. However, ladle re-scheduling is particularly special. In steelmaking and continuous casting production processes, the starting time delay frequently occurs, which may lead to casting break or processing conflict. Accordingly, the static scheduling plan becomes unrealisable. The requirements of the heat processing equipment (converter, refining furnace and continuous casting machine) are met according to the production equipment scheduling plan. A ladle carrying molten steel is selected, and the route of transporting the ladle is determined under the conditions of the start and end times of the equipment. The existing optimal scheduling methods are difficult to adopt because ladle re-scheduling must meet multiple conflicting goals and constraints.
Ladle is the equipment for loading molten steel, and it serves all the processing stages in the SCC production. This equipment runs through the whole process from converter tapping, refining and continuous casting machine to casting billet formation. In the SCC process research, researchers pay more attention to the structure and material of the ladle to reduce heat loss during service. The ladle, which is a part of the refining equipment outside the furnace, needs to solve two other problems: ○ ladle matching and □ transportation scheduling problem. Otherwise, the refining process cannot be normally carried out according to the production equipment scheduling plan.

A three-step heuristic algorithm based on the model features for ladle scheduling was proposed [13]. A multi-objective soft scheduling (MOSS) is proposed to overcome the uncertain scheduling problem arising from the SCC manufacturing system [14]. The steel plant’s computerised scheduling model for the continuous casting process was introduced [15]. A steel ladle scheduling system with an integrated system was created [16]. The influence of ladle on steelmaking scheduling was analysed [17]. The ladle operation and the calculation of the number of ladles were thought to be reasonable [18].

The researcher simplified the SCC production scheduling by using constraint satisfaction methods to address re-scheduling equipment failures and quality disturbance [19]. The utility function and stability were used to judge the rescheduling result [20]. A multi-stage dynamic soft scheduling algorithm based on an improved differential evolution was proposed [5].

The main focuses of the literature on ladle management and more related references in the industrial fields [21–27], with an emphasis on ladle turnover, are to simplify the constraints related to ladle selection and study the simplified ladle production model. The actual production of the best matching ladle is difficult to meet when the ladle matching complex constraints are not fully considered. How to carry out effective ladle re-scheduling is a problem that must be solved in every steel mill’s workshop production scheduling. The study of ladle re-scheduling in steel mill workshops is inextricably linked to static scheduling; it is the only way to ensure that good production scheduling is carried out.

3 Analysis of ladle scheduling problems

The modern large-scale SCC production process is composed of multiple converters, refining furnaces, tundishes, continuous casters and ladles loaded with molten steel. The current SCC production re-scheduling method is only a study of simple production modes, such as two electric arc furnaces–two refining furnaces–two continuous casters and two converters–three refining furnaces–two continuous casting machines. No research has been conducted on the more complex multiple converters, refining furnaces and continuous casting machines in the actual production process and the rescheduling problem in the case of multiple refining methods. Mathematical planning methods and intelligent algorithms cannot quickly obtain the optimal solution while simultaneously satisfying the above-mentioned constraints. Accordingly, experienced dispatch engineers can only rely on experience to formulate re-dispatch plans. When the fire start time delay is disrupted, the dispatch engineer cannot timely compile the rescheduling plan, and the number of decision-making furnaces is small. This phenomenon leads to a long waiting time for the overall rescheduling result.

According to the smelting process criteria, no ladle can be loaded with any type of molten steel. Steel grades have material, age, temperature and ladle nozzle limitations. Some of these constraints can be quantified, such as ladle age, temperature and nozzle, while others are not, such as the corrosion of molten steel to the ladle’s material. The steelmaking–refining–continuous casting production process has discrete and continuous manufacturing features. Therefore, the problem of steelmaking–refining–continuous casting ladle path planning is a multi-objective, nonlinear hybrid programming model, and the conflicting objective functions are difficult to simultaneously meet.

The overall scheduling strategy of steelmaking–refining–continuous casting is shown in Fig. 2. Given that the production process path and the heat treatment time are fixed constants, the SCC production static scheduling is based on the specified pouring time on the continuous casting machine on time, continuous heat casting in the same pouring time and on the same equipment. The goal is to prevent conflict between adjacent heat. Then, the heat processing equipment, refining and heat start time in the converter, refining furnace and continuous casting machine are determined, and a schedule is formed.

In view of the uncertain factors that often appear during manufacturing (such as transportation delays, processing overtime and the need to adjust the plan for substandard quality), a corresponding rescheduling plan according to the working conditions must be proposed. Generating a re-scheduling plan requires changing the constraints in the scheduling model according to the current status of the workshop and recalculating. However, if some parameters (such as completion, processing and transportation times) are only set according to standard values, the modified plan will be rescheduled again.

Re-scheduling is based on the original static scheduling plan. The heat’s processing status is known, and the production process path is unaltered. The heat processing and
transportation times on the converter and refining furnace are well-known and consistent. The performance indexes are two types of adjacent heat on the same equipment that do not produce operational conflicts. The heat within the casting cycle is continuously cast. Moreover, the heat processing time on the continuous casting machine does not exceed the set limit.

Re-scheduling is conducted to determine the processing equipment and start time of the unprocessed heat in each cast. This process is also carried out to identify the start and end times of the unprocessed heat on the continuous caster and the end time of the processed heat on the continuous caster. Then, a new scheduling plan is formed.

The ladle matching directly affects the temperature and composition of heat. This condition indirectly affects the heat processing time and brings disturbance to the scheduling plan. Ladle matching is based on the steelmaking–refining–continuous scheduling plan and the ladle state. A suitable ladle is determined from the ladle used on site for each furnace. The ladle path is compiled for the heat to determine all the transportation sections used in the production. The crane running track is divided by whether the crane can set the ladle as the separation in the transportation section. Then, the ladle transportation route plan that meets the site requirements is determined.

If a satisfactory solution cannot be obtained, then the heat processing time or equipment is adjusted through a human–computer interaction until a satisfactory solution is obtained.

In summary, the ladle re-scheduling problem is a large-scale combinatorial optimisation problem with multiple objectives and constraints. At present, steelmaking plants can only use manual or telephone methods to guide the ladle dispatch. This situation results in inefficient scheduling plan execution, which can easily lead to extra furnace redundancy time and untimely ladle transportation. The temperature of the molten steel decreases, thus necessitating more heating, and punctual pouring is difficult to achieve.

This work considers multiple refining to meet the requirements of continuous casting and ladle production technology. A SCC ladle re-scheduling model is established on the basis of satisfying the process sequence, equipment capacity, pouring time, processing time and transportation time constraints. This work studies the algorithm for solving ladle re-scheduling in a dynamic environment, conducts ladle re-scheduling and revises the production equipment scheduling plan. The start and end processing times of the converter, refining, and ladle are optimised. An accurate production equipment re-scheduling plan is obtained, and ladle scheduling is carried out. Finally, this work is verified through actual industrial cases.
4 Modelling of the ladle re-scheduling problem

The problem of ladle re-scheduling is divided into two parts: (1) ladle re-scheduling and (2) ladle optimisation scheduling. Firstly, the static plan is re-scheduling based on the actual production operation. On this basis, the ladle scheduling is optimised. These processes are described as follows.

4.1 Re-scheduling adjustment modelling

4.1.1 Symbol definition

| Index: |
|--------|
| i      | Cast serial number |
| j      | Heat serial number |
| g      | Device type number |
| \( k_i \) | k th device of type g |
| \( m_{ij} \) | b th device of device type g |
| \( \Omega_i \) | The heat that has not been started in the continuous casting stage in the \( i \)th cast is set |

| Parameter: |
|-----------|
| \( N \) | Total number of cast |
| \( J_i \) | Total heat number of cast \( i \) |
| \( L_{ij} \) | j th heat of cast \( i \) |
| \( K_g \) | Total number of devices of type g |
| \( G_{ij} \) | The production process paths for the \( j \)th heat of cast \( i \), \( G_{ij} = \{ g_{i1}, g_{i2}, g_{i3}, \ldots, g_{in} \} \), is set, where \( g_{ij} \) represents the type of processing equipment in the first stage of the \( j \)th heat of cast \( i \), and so on |
| \( \Pi_i \) | The heat processing sequence of cast \( i \), \( \Pi_i = \{ L_{i1}, L_{i2}, \ldots, L_{ij}, \ldots \} \), is set |
| \( k^*_{ij} \) | Sequence of heat processed by equipment |
| \( T_{\min g} \) | Minimum processing time of type g |
| \( T_{\max g} \) | Maximum processing time of type g |
| \( T_{\max k} \) | Transportation time from the \( k \)th equipment of type g to the \( k+1 \)th equipment of type g + 1 |
| \( x_{ij}^g(k_g) \) | The start time of heat \( L_{ij} \) on equipment \( k_g \) and \( k^*_{ij} \) is a known quantity |
| \( y_{ij}^g(k_g) \) | The end time of heat \( L_{ij} \) on equipment \( k_g \) and \( k^*_{ij} \) is a known quantity |
| \( \beta_{ij}^g(k_g) \) | Processing status of heat \( L_{ij} \) on equipment \( k_g \) when not working, \( \beta_{ij}^g(k_g) = 0 \) when processing, \( \beta_{ij}^g(k_g) = 1 \) when finished and \( \beta_{ij}^g(k_g) = 2 \) |
| \( t_r \) | Re-scheduling moment |
| \( x_{ij}(k_g) \) | Start time of heat \( L_{ij} \) on equipment \( k_g \) |
| \( y_{ij}(k_g) \) | End time of heat \( L_{ij} \) on equipment \( k_g \) |

4.1.2 Performance indicators

The temperature of molten steel in the ladle is one of the process parameters that need to be controlled during the steelmaking process. If the temperature of the molten steel is low, then its processing time on the refining equipment must be extended, or other refining equipment for heating treatment must be added. This approach will increase the production cycle and seriously affect production. Therefore, the interval time between each process in the production must be strictly controlled. Specifically, the total waiting time of the heat between adjacent processing equipment must be as small as possible.

The difference between the start time \( x_{ij}(k_g) \) and the completion time \( y_{ij}(k_{g-1}) \) and the transportation time between equipment \( T_{k_g-k_g-1} \), \( x_{ij}(k_g) - y_{ij}(k_{g-1}) - T_{k_g-k_g-1} \), which is the processing waiting time \( W_{ij}(k_g) \) of heat \( L_{ij} \) between stages \( g - 1 \) and \( g \) is as follows:

\[
W_{ij}(k_g) = x_{ij}(k_g) - y_{ij}(k_{g-1}) - T_{k_g-k_g-1}^k \quad i = 1, \ldots, N; L_{ij} \in \Omega_i; g = 2, \ldots, 5.
\]

The sum of the processing waiting time \( W_{ij} \) of the heat \( L_{ij} \) in all adjacent processes is obtained as follows:

\[
W_{ij} = \sum_{k=2}^{5} W_{ij}(k_g) = \sum_{k=2}^{5} (x_{ij}(k_g) - y_{ij}(k_{g-1}) - T_{k_g-k_g-1}^k) \quad i = 1, \ldots, N; L_{ij} \in \Omega_i.
\]

Therefore, the total processing waiting time \( W \) of heat in the adjacent processes is \( W = \sum_{i=1}^{N} \sum_{L_{ij} \in \Omega_i} W_{ij} \). The optimisation goal is to minimise \( W \), that is, to establish the following performance indicators:

\[
\min W = \sum_{i=1}^{N} \sum_{L_{ij} \in \Omega_i} W_{ij} = \sum_{i=1}^{N} \sum_{L_{ij} \in \Omega_i} \sum_{k=2}^{5} (x_{ij}(k_g) - y_{ij}(k_{g-1}) - T_{k_g-k_g-1}^k) \quad i = 1, \ldots, N; L_{ij} \in \Omega_i.
\]

4.1.3 Constraints

1. The heat in the same casting must follow the casting order.
   \( x_{i,j+1}(k_g) \) must be equal to \( y_{ij}(k_g) \) as much as possible to make continuous casting of adjacent heat \( L_{ij} \) and \( L_{i,j+1} \) in the same cast, namely,

\[
x_{i,j+1}(k_g) - y_{ij}(k_g) = 0 \quad i = 1, 2, 3; j = 1, \ldots, I - 1.
\]
because the processing time of heat $L_y$ on the continuous caster is within the range of $[T_{S_5}^{min}, T_{S_5}^{max}]$, namely:

$$y_y(k_5) - x_y(k_5) \leq T_{S_5}^{max}$$
$$y_y(k_5) - x_y(k_5) \geq T_{S_5}^{min}.$$  \tag{5}

When the starting time interval $x_{i,j+1}(k_5) - y_y(k_5)$ of heat $L_y$ and $L_{i,j+1}$ is less than or equal to the maximum processing time $T_{S_5}^{max}$:

$$x_{i,j+1}(k_5) - y_y(k_5) \leq T_{S_5}^{max}.$$  \tag{6}

2. Heat processing sequence constraint: each stage of heat processing must be processed in sequence according to the order specified by the production process.

To ensure that the heat is processed in the order specified by the production process path, heat $L_y$ can be processed at stage $g + 1$ only when $L_y$ is completed in stage $g$ and reaches stage $g + 1$ after being transported. Specifically, $x_y(k_{g+1}) - y_y(k_g) - T_{k_g}^{k_{g+1}}$ must be greater than or equal to zero, namely:

$$x_y(k_{g+1}) - y_y(k_g) - T_{k_g}^{k_{g+1}} \geq 0$$
$$i = 1, 2, 3; j = 1, \ldots, J_i; g = 1, \ldots, \left| G_y \right| - 1.$$  \tag{7}

3. Conflict constraints that cannot occur between different heat processed on the same equipment

Heat operating conflict means that two heat simultaneously occupy the same equipment resource. The six types of on-site work time conflicts are as follows (Fig. 3):

(A) Front cross conflict: The newly arranged heat is operated before the scheduled heat, and the operating time of the two is partially overlapped, as shown in Fig. 3a.

(B) Post-cross conflict: The newly arranged heat is operated after the scheduled heat, and the operating time of the two partially overlaps, as shown in Fig. 3b.

(C) Contain conflict: the newly arranged heat is operated after the arranged heat, and the operating time overlaps, as shown in Fig. 3c.

(D) Outside containing conflict: the newly arranged heat is operated before the scheduled heat, and the operating time overlaps, as shown in Fig. 3d.

(E) Complete conflict: The operating time of the newly arranged heat completely overlaps, as shown in Fig. 3e.

\[
\text{min}(y_y(k_4), y_{i,d_1}(k_4)) - \text{max}(x_y(k_4), x_{i,d_1}(k_4)) \leq 0 \quad \text{if } L_y, L_{i,d_1} \in \Omega_{R_{i,d}} \quad L_y \neq L_{i,d_1}. \tag{9}
\]

The number of processing equipment is varied and combined with the on-site situation depending on whether the heat processing equipment is known. The three situations for analysis of heat operating conflicts between different heat processed on the same equipment are as follows:

(I) Adjacent heat on the same continuous casting machine cannot produce operating time conflicts.

The heat immediately after heat $L_y$ on the continuous casting machine is $L_{i,j+1}$. When $x_{i,j+1}(k_5) - y_y(k_5) \geq 0$, heat $L_{i,j+1}$ and $L_y$ will not conflict. Thus:

$$x_{i,j+1}(k_5) - y_y(k_5) \geq 0 \quad i = 1, 2, 3; j = 1, \ldots, J_i - 1.$$  \tag{8}

(II) In any type of equipment, only one equipment (IR_UT) adjacent to the heat cannot produce the operating time conflict.

Heat that needs to be processed by IR_UT can be obtained, assuming that the heat production process path is known. $\Omega_{R_{i,d}}$ is assumed as the set of heat processed by IR_UT, and the amount of heat contained in it is $N_{IR_U T}$. Given that IR_UT has only one device for the heat in $N_{IR_U T}$, its start and completion times on IR_UT can be expressed as $x_y(k_4)$ and $y_y(k_3)$. In any two heat in $\Omega_{R_{i,d}} (IR_{UL})$ that cannot conflict, the description is as follows:

\[
\text{min}(y_y(k_4), y_{i,d_1}(k_4)) - \text{max}(x_y(k_4), x_{i,d_1}(k_4)) \leq 0 \quad \text{if } L_y, L_{i,d_1} \in \Omega_{R_{i,d}} \quad L_y \neq L_{i,d_1}. \tag{9}
\]

\[
\text{min}(y_y(k_4), y_{i,d_1}(k_4)) - \text{max}(x_y(k_4), x_{i,d_1}(k_4)) \leq 0 \quad \text{if } L_y, L_{i,d_1} \in \Omega_{R_{i,d}} \quad L_y \neq L_{i,d_1}. \tag{9}
\]
(III) On each equipment (RH) with multiple parallel machines, no time conflict can be generated for adjacent heat.

Assuming that the heat production process path is known, heat that needs to be processed by RH can be obtained. The research is based on the data of a steel company in Shanghai, China, which has three RH refining furnaces; hence, $k_1 = 1$, or 2 or 3. This study assumes that $\Omega_{RH}$ is the set of all heat processed by RH, and the number of heat it contains is $N_{RH}$. Only three RHs are present on site. The start and completion times on RH of the heat in $\Omega_{RH}$ can be expressed as $x_y(k_2)$ and $y_j(k_2)$, respectively. The description of any two heat in $\Omega_{RH}$ that cannot conflict is as follows:

$$
\min(x_y(k_2), y_{i,j}(k_2)) - \max(x_y(k_2), x_{i,j}(k_2)) \leq 0
$$

$L_{ij}, L_{i,j} \in \Omega_{RH}$, and $L_{ij} \neq L_{i,j}, k_1 = 1, or 2 or 3$.

(10)

4. Heat processing time constraint
The processing time meets:

$$
\begin{align*}
&y_j(k_2) - x_y(k_2) \leq T_{\text{max}}^m \\
&y_j(k_2) - x_y(k_2) \geq T_{\text{min}}^m.
\end{align*}
$$

(11)

5. Constraint on the heat in the continuous casting process
During the entire re-scheduling, the continuous caster must be in the initial scheduling plan, namely:

$$
k_{[g]} = m^0_{i,j}, [g_i] i = 1, 2, 3; j = 1, ..., J_i.
$$

(12)

6. Constraint on the casting sequence of the heat in the same cast
In a given casting schedule, the processing sequence of the heat in the same cast on the continuous caster is known, namely:

$$
x_{i,j+1}(k_{[g_i,j]}) - y_j(k_{[g_i]}) \geq 0 i = 1, 2, 3; j = 1, ..., J_i.
$$

(13)

7. Constraint on the processing equipment at each stage of the heat
A device type contains multiple devices with the same function. Heat can only be processed on one of the equipment in each stage, namely:

$$
k_g = \text{ENUM}\{ 1, ..., K_x \mid x_y(k_g) \} i = 1, 2, 3; j = 1, ..., J_i; g_i \in G_y.
$$

(14)

8. Constraints on the heat processing equipment, start-up time and completion time in the process
When heat $L_{ij}$ has been processed in a certain stage $g$ ($L_{ij}$), the processing equipment, start time and completion time of heat $L_{ij}$ in stage $g$ cannot be changed, namely:

$$
k_g = m^j_i(k_g) i = 1, 2, 3; j = 1, ..., J_i; g = 1, ..., |G_y|; \beta_j(k_g) = 2
$$

(15)

$$
x_y(k_g) = x^0_y(k_g) i = 1, 2, 3; j = 1, ..., J_i; g = 1, ..., |G_y|; \beta_j(k_g) = 2
$$

(16)

$$
y_j(k_g) = y^0_j(k_g) i = 1, 2, 3; j = 1, ..., J_i; g = 1, ..., |G_y|; \beta_j(k_g) = 2
$$

(17)

9. Constraint on the processing equipment and start-up time of the processing heat
When $L_{ij}$ is processing ($\beta_j(k_g) = 1), the processing equipment and start time cannot be changed, namely:

$$
k_g = m^j_i(k_g) i = 1, 2, 3; j = 1, ..., J_i; g = 1, ..., |G_y|; \beta_j(k_g) = 1
$$

(18)

$$
x_y(k_g) = x^0_y(k_g) i = 1, 2, 3; j = 1, ..., J_i; g = 1, ..., |G_y|; \beta_j(k_g) = 1
$$

(19)

4.1.4 Decision variables

The variables that need to be considered when rescheduling are as follows: (1) processing equipment, start time and completion time of heat in the unstarted process; and (2) the completion time of the heat in the process. Therefore, the following decision variables are selected:

$$
x_y(k_g) is the time decision variable for re-scheduling, and it is an integer variable and the start time of $L_{ij}$ on equipment $k_g$.

$$
y_j(k_g) is the time decision variable for re-scheduling, and it is an integer variable and the end time of $L_{ij}$ on equipment $k_g$.

4.2 Ladle optimal scheduling model

4.2.1 Optimisation target selection

The first-order rule learning is used to learn the training set, ladle matching attribute set $A = \{a_1, a_2, ..., a_{|A|}\} = \{\text{Steel species}, \text{ladle number}, \ldots, \text{empty ladle weight}\}$ (Table 1).

The typical and random data are selected to build the ladle training set, in which the ratio of typical and random data is 1:3 (Table 2). The data conversion and the establishment of the relational data are shown in Table 3.

The relational data sample is the atomic formula transformed from the sample analogy for ‘better’ and ‘better’. Decarburisation ladle matching initial empty rule is applied using First-Order Inductive Learner (FOIL) for rule-based learning:

$$
\text{better}(X, Y) \leftarrow .
$$

(20)

‘FOIL Gain’ is used to select the text:

$$
F_{\text{Gain}} = \hat{m}_+ \times \left( \log_2 \frac{\hat{m}_+}{\hat{m}_-} - \log_2 \frac{\hat{m}_+}{\hat{m}_+ + \hat{m}_-} \right)
$$

(21)
where $\hat{m}_+$ and $\hat{m}_-$ are the positive and negative examples covered by the new rules after adding the candidate words; and $\hat{m}_+$ and $\hat{m}_-$ are the number of positive and negative examples covered by the original rules. We select the typical positive and negative samples to learn the minimum coverage of all the attributes of the sample as the optimal target of ladle matching according to field experts.

### 4.2.2 Ladle optimal scheduling model

#### 4.2.2.1 Performance indicator

1. Ladle temperature
   \[
   \max T(k) \tag{22}
   \]
2. Number of ladle used
   \[
   \max L(k) \tag{23}
   \]
3. Transport time

#### 4.2.2.2 Constraints

1. Crane weight
   The maximum load of the crane of path $k_7$ selected by heat $L_{ij}$ is greater than the weight of the molten steel of $L_{ij}$.
   \[
   Lo_{ij} < Lo(k_7). \tag{26}
   \]
2. Crane operating speed
   The operating speed and distance of the crane shall not exceed the time requirements specified in the scheduling plan.

### Table 1 Definition of the ladle matching properties

| Attributes                        | Symbol | Variable description                                      |
|-----------------------------------|--------|----------------------------------------------------------|
| Steel species                     | $S_k$  | Furnace number of the process                            |
| Ladle number                      | $k$    | Ladle serial number                                      |
| Ladle bales regulation            | $R_m$  | Ladle bales m-bit regulation                             |
| Ladle status                      | $S^e_m$| $m$-bit ladle $k$ state                                  |
| At the end of the cold steel volume| $R(k)$ | Ladle $k$ remaining molten steel                         |
| Ladle temperature                 | $T(k)$ | Temperature of ladle $k$                                 |
| Ladle material                    | $M(k)$ | Ladle $k$ material                                       |
| Number of sewers                  | $D(k)$ | Number of ladle $k$’s outlet                             |
| Usage count                       | $L(k)$ | Number of ladle $k$ to use                               |
| Supra number of use (East)        | $U^e_k$| Ladle $k$ east outlet number of uses                     |
| Number of uses of the outlet (West)| $U^w_k$| Ladle $k$ West catchment use frequency                   |
| Skate usage (East)                | $S^e_k$| Ladle $k$ East skateboard use frequency                  |
| Number of skateboards (west)      | $S^w_k$| Ladle $k$ West slide use frequency                       |
| Drainage (East)                   | $M^e_k$| Ladle $k$ drainage material (East) of the material       |
| Drainage (West)                   | $M^w_k$| Ladle $k$ drainage material (West)                       |
| Frame usage (East)                | $F^e_k$| Ladle $k$ frame (East) use frequency                     |
| Frame usage (West)                | $F^w_k$| Ladle $k$ frame (West) for the number of uses            |
| Empty ladle weight                | $E(k)$ | Ladle $k$ empty ladle weight                             |

\[
\min \sum tr_{ij} \left(k_{g(\theta)}, k_{g(\theta+1)} \right) \tag{24}
\]

4. Start work on time as much as possible
   \[
   \max \sum \varepsilon^k_{ij}. \tag{25}
   \]

### Table 2 Data set of ladle matching

| Steel species | Refining | Temperature | Ladle material | Ladle status | Drainage material (East) | Drainage material (West) | Empty ladle weight | Available |
|---------------|----------|-------------|----------------|--------------|--------------------------|-------------------------|--------------------|-----------|
| 1 AK202204    | R        | >1341       | Overall ladle  | Run          | Forsterite               | Forsterite              | 136                | Can       |
| 2 AP1055E5    | R        | >1126       | Magnesium aluminium | Preparation | Silicon                  | Silicon                | 125                | Can       |
| 3 AP1055E5    | R        | >1457       | Aluminium magnesium carbon | Dry          | Zirconium                | Zirconium              | 145                | No        |
| 4 AP1055E5    | R        | >1600       | Overall ladle  | Repair       | Chromium                 | Chromium               | 142                | No        |
| 5 AP1055E5    | R        | <879        | Magnesium aluminium | Run          | Forsterite               | Forsterite             | 128                | No        |
| 6 XK437311    | LR       | <1379       | Overall ladle  | Preparation  | Forsterite               | Forsterite             | N/A                | Can       |
The SCC production process consists of multiple converters, refining furnaces, continuous casting machines and refining process methods, resulting in the continuous casting of adjacent heat in the same casting cycle on the continuous casting process. Engineers are required to reschedule any deviation from the static scheduling plan, then the processing equipment one by one, and the new starting time of the heat on the equipment is given. If the production process greatly deviates from the static scheduling plan, then the processing equipment, start time and completion time of the ‘unprocessed’ heat are manually re-determined in the steelmaking and refining procedures. Due to many constraints in ladle re-scheduling, there are processes that have been processed, processes that are being processed, and processes that have not been processed for a single heat in the production process; there are processes that have been processed, heats that are being processed, adjacent heat has many conflicting hard constraints. The ladle re-scheduling problem model is a mixed integer programming model because its decision variables are divided into equipment (integer quantities) and time (continuous quantities) variables. Falling into local minima or slow solution speed is easy as the scale of the model increases, such as the cutting plane method, branch and bound method, and Lagrangian method, when solving this mixed integer programming model in which the continuous variables depend on the integer variables. The needs of the site in terms of solution accuracy and efficiency are difficult to meet. Intelligent optimization methods (such as genetic algorithm, particle swarm algorithm and ant colony algorithm) can solve this mixed integer programming model in which continuous variables depend on integer variables. However, the intelligent optimization method has the shortcomings of easily falling into local minima and slow solving speed. The on-site requirements for solving scheduling problems in terms of accuracy and efficiency are difficult to meet. Therefore, a fast optimized method for determining working conditions must be developed to solve the SCC ladle re-scheduling problem. This work uses a BP neural network to quickly estimate rescheduling algorithm parameters for reducing the number of rescheduling.

Firstly, the neural network is trained according to the scheduling knowledge prepared by the manufacturing system. When an uncertain event occurs, the current changed system state is then used as the input of the trained neural network, and the expected rescheduling parameters are calculated through the BP neural network, as shown in Fig. 4.

The processing equipment and operating time specified in the static scheduling plan cannot be easily followed in the actual production process. Engineers are required to re-schedule any time according to production disturbances. To ensure continuous casting, manual adjustment is carried out to adjust the starting time of the subsequent stage of the disturbance heat on the equipment one by one, and the new starting time of the heat on the equipment is given. If the production process greatly deviates from the static scheduling plan, then the processing equipment, start time and completion time of the ‘unprocessed’ heat are manually re-determined in the steelmaking and refining procedures. Due to many constraints in ladle re-scheduling, there are processes that have been processed, processes that are being processed, and processes that have not been processed for a single heat in the production process; there are processes that have been processed, heats that are being processed,

### Table 3 Data relationship of ladle matching

| Example | Better (1,3) | Better (1,4) | Better (1,5) | Better (1,6) |
|---------|-------------|-------------|-------------|-------------|
|         | “Better (3,1)” | “Better (4,1)” | “Better (5,1)” | “Better (6,1)” |

![Image](image-url)

\[
\frac{l(k)}{v} + 2d < tr(k; k_{\theta}, k_{\theta+1}).
\]  

(27)

3. Ladle temperature
   The temperature of the ladle cannot exceed the upper and lower limits of the process requirements.
   \[
   T_{\min}^i \leq T(k) \leq T_{\max}^i.
   \]  

(28)

4. Crane position
   The crane \( k \) runs within a unit of time to meet:
   \[
   P_{l_i}^k + v \geq P_{l_i}^{k+1} \geq P_{l_i}^k - v.
   \]  

(29)

5. Matching crane
   Every \( O_{\theta} \) should be allocated to a crane. A crane can handle at most one transportation task.
   \[
   \sum y_{\theta}^i = 1, \sum y_{\theta}^j \leq 1.
   \]  

(30)

6. Transportation safety
   The minimum distance between two adjacent cranes is as follows:
   \[
   \left| P_{l_i}^k - P_{l_i}^k \right| \geq \delta.
   \]  

(31)

#### 4.2.2.3 Decision variables

1. A dephosphorisation ladle is chosen for each furnace \( L_{ij} \) via dephosphorisation:
   \[
   \text{IF } G_{ij} = 1 \text{ THEN } \exists! L_{ij,k} = 1.
   \]  

(32)

2. A decarburisation ladle is chosen for each furnace \( L_{ij} \)
   \[
   \exists! L_{ij,k} = 1.
   \]  

(33)

#### 5 Ladle re-scheduling algorithm

The SCC production process consists of multiple converters, refining furnaces, continuous casting machines and refining process methods, resulting in the continuous casting of adjacent heat in the same casting cycle on the continuous casting machine and the same equipment. The non-conflict operation of...
and processes that have been processed for multiple heats. The amount of heat that is yet to be processed and the constraints under different production conditions are constantly changing; thus, manual adjustments in a short period of time cannot provide optimal adjustment results. The current re-dispatch can only rely on experienced dispatch engineers to adjust the plan based on experience due to the lack of fast and optimised adjustment methods. The ladle re-scheduling algorithm is established to solve these problems.

The ladle re-scheduling algorithm is divided into two parts: the re-scheduling algorithm and the ladle optimisation scheduling algorithm, which are described as follows.

### 5.1 Re-scheduling algorithm

#### 5.1.1 Decision algorithm for rescheduling heat

The re-scheduling objects are unfinished heat. Let $\Omega$ be the set of heat that need to be re-scheduled in the initial scheduling plan set $\Omega^0$. Then, the decision algorithm for rescheduling heat is as follows:

#### 5.1.2 Decision-making algorithm for the heat processing equipment

If the heat $L_{ij}$ is assigned to the equipment for processing, then the heat that may conflict with $L_{ij}$ on the equipment is recorded as $L_{i_1,j_1}$. Let $F_m$ be the conflict value of the operating time of the heat $L_{ij}$ and $L_{i_1,j_1}$ on equipment $m$:

$$F_m = \max\{x_{ijk}, x_{i_1,j_1,k_1}\} - \min\{y_{ijk}, y_{i_1,j_1,k_1}\}, \quad L_{ij}, L_{i_1,j_1} \in \Omega.$$  

(34)

**Algorithm 1: Decision algorithm for re-scheduling heat**

- **Step 1:** Obtain the initial scheduling plan set $\Omega^0$ and the processing state $\beta_{i,j,e_{i}}$ of the batches in $\Omega^0$ in the continuous casting process. Let the set of rescheduling batches $\Omega = \Phi$;
- **Step 2:** Let $i = 1$;
- **Step 3:** Let $j = 1$;
- **Step 4:** If $\beta_{i,j,e_{ij}} = 0$, then $\Omega = \Omega + \{L_{ij}\};$
- **Step 5:** If $j = J$, then go to **Step 6**; else, $j = j + 1$, go to **Step 4**;
- **Step 6:** If $i = 3$, then go to **Step 7**; else, $i = i + 1$, go to **Step 3**;
- **Step 7:** end, get $\Omega$. 

---

**Fig. 4** Parameter estimation based on the BP neural network

**Fig. 5** Solving the decision variables of charge equipment
3. Solve the decision variables of the heat equipment based on the rules of minimum heat conflict and transportation times between equipment: the decision variables are solved on the basis of the minimum heat operating conflict time rule, minimum transportation time between equipment rules, minimum number of equipment processing furnaces and random selection rules. A heuristic method is used to make decisions on the equipment decision variables of the furnace in the unstarted stage.

5.1.2.1 Based on the processing status of the heat to determine the heat stage of the equipment decision

Let $\alpha_{ijk}$ be the variable of whether heat $L_{ij}$ can be adjusted in stage $k$: if the equipment can be adjusted, then $\alpha_{ijk} = 1$; otherwise, $\alpha_{ijk} = 0$

1. The processing equipment (continuous caster) of the heat in the continuous casting process has been designated, and it cannot be changed during the re-scheduling process.

$$\alpha_{i,x_j} = 0 \quad L_{ij} \in \Omega$$ (35)

2. When a heat is being processed or has been processed in a certain procedure, the re-scheduling can no longer change the processing equipment of the heat in that process:

$$\alpha_{ik} = 0 \quad L_{ij} \in \Omega;k = 1, \ldots, \varepsilon_{ij} - 1; \beta_{ijk} = 1,2$$ (36)

3. When the heat is not started in the non-continuous casting process, re-scheduling can adjust the processing equipment of the heat in the process; that is, when the heat $L_{ij}$ is in the stage $k (k \neq \varepsilon_{ij})$, the processing state $\beta_{ijk} = 0$. The rescheduling method can reassign its equipment.

Algorithm 2: Heat batching and operation sorting algorithm

**Step 1:** Obtain the information of the initial scheduling plan: the total number of cast $N$, the total number of heat of the $i$th cast $J_i$, the completion time of the heat $L_{ij}$ on the continuous caster $e_{t_{ij},x_j}$ and rescheduling time $t_r$; then, determine the set of rescheduling heat $\Omega$.

**Step 2:** Let $\Omega_1 = \Phi, \Omega_2 = \Phi, \Omega_1 = \Phi, \Omega_2 = \Phi, \Omega_3 = \Phi$

**Step 3:** All heat $L_{ij} \in \Omega$:

- If $e_{ij} \leq t_r$, then $\Omega_1 = \Omega_1 + \{L_{ij}\}$; else, $\Omega_2 = \Omega_2 + \{L_{ij}\}$.

**Step 4:** In all heat $L_{ij} \in \Omega_1$:

- (a) Let $k = 1$;
- (b) If $k < \varepsilon_{ij} + 1$, then $O_1 = O_1 + \{\alpha_{ijk}\}$;
- (c) $k = k + 1$, go to Step 4(b)

**Step 5:** In all heat $L_{ij} \in \Omega_2$:

- (a) Let $k = 1$;
- (b) If $k < \varepsilon_{ij} + 1$;
- (c) If $k = \varepsilon_{ij}$, then $O_2 = O_2 + \{\alpha_{ijk}\}$; else, $O_2 = O_2 + \{\alpha_{ijk}\}$
- (d) $k = k + 1$, go to Step 5(b).

**Step 6:** Arrange all operations in $O_1$ in an ascending order of start time.

**Step 7:** Arrange all operations in $O_2$ in an ascending order of start time.

**Step 8:** Arrange all operations in $O_3$ in a descending order of start time.

$$\alpha_{ik} = 1L_{ij} \in \Omega;k = 1, \ldots, \varepsilon_{ij} - 1; \beta_{ijk} = 0$$ (37)

5.1.2.2 Based on the start-up time of heat to sort decisions

The heat in the rescheduled heat object set is divided into two batches, namely, processing and unstarted heat, denoted by $\Omega_1$ and $\Omega_2$.

The operations are processed or completed in batch $\Omega_1$ of the processing heat. The processing equipment and start time of these operations in the process cannot be modified during re-scheduling. When adjusting the operating time of the unstarted operation in $\Omega_1$, the operating time can only be moved backward to meet the processing sequence constraints. Therefore, the operations are sequentially performed in the order of the start time of each operation in $\Omega_1$ from early to late. Let $O_1$ be the set of operations sorted by the start time of all operations in $\Omega_1$ from early to late.

In the batch of unstarted heat $\Omega_2$, the start time of the unstarted heat on the continuous caster should be the same as that of the previous heat processed on the same continuous caster due to the continuous casting constraints of adjacent heat in the same casting. The completion time is equal. Firstly, the start and completion times of the $\Omega_2$ heat on the continuous caster are calculated according to the completion time of $\Omega_1$ heat on the continuous caster. Then, the start and end times of the $\Omega_2$ heat in the refining and converter stages are calculated in reverse. Let $O_2$ be the set of operations in which all operations of the $\Omega_2$ heat on the continuous caster are sorted from early to late. $O_3$ is all operations of the $\Omega_2$ heat in the refining and converter stages. The batching and operation sorting algorithm is as follows:
5.1.2.3 Solve the decision variables based on the rules of minimum heat conflict time and minimum transportation time

The calculation of heat equipment assignment variable is to select equipment in sequence according to the order of $O_1 + O_2 + O_3$ to reduce the waiting time of heat between adjacent equipment. This study proposes a priority-based equipment assignment method: minimum conflict time between operations, minimum transportation time between equipment, minimum number of equipment processing furnaces and random selection.

1. Minimum conflict time between operations

This study assumes the presence of operation $o_{i,j,k}$ on device $m$. When operation $o_{i,j,k}$ is also arranged on device $m$, $F_m > 0$, $o_{i,j,k}$ and $o_{i',j',k'}$ have a job conflict on device $m$. If $o_{i,j,k} \in O_1$, then $o_{i,j,k}$ is processed after $o_{i',j',k'}$, as shown in Fig. 6a. Conflict time $F_m = Y_{i,j,k} - X_{i',j',k'}$. At this time, only the operation time of $o_{i,j,k}$ can be shifted backward by $F_m$. If $o_{i,j,k} \in O_3$, and $o_{i',j',k'} \in O_3$, then $o_{i,j,k}$ is processed before $o_{i',j',k'}$, as shown in Fig. 6b; $F_m = Y_{i,j,k} - X_{i',j',k'}$. At this time, the working time of $o_{i,j,k}$ is shifted forward by $F_m$.

When rescheduling, the minimum operating time conflict rule between operations is adopted. The equipment that minimises the operating time conflict is selected from the equipment set $\Pi_{o_{i,j,k}}$ that can process $o_{i,j,k}$, namely:

$$z^m_{o_{i,j,k}} = 1m = \arg\min \{ F_m | m \in \Pi_{o_{i,j,k}} \}$$  (38)

2. Shortest transportation time

$$z^m_{o_{i,j,k}} = 1m = \arg\min \{ T_{m,m'} | m \in \Pi_{o_{i,j,k}} \}$$  (39)

3. Minimum number of equipment processing furnaces

$$z^m_{o_{i,j,k}} = 1m = \arg\min \{ H_m | m \in \Pi_{o_{i,j,k}} \}$$  (40)

4. Random selection

The random selection rule refers to randomly selecting a device when assigning equipment to $o_{i,j,k}$, namely:

$$z^m_{o_{i,j,k}} = 1m = \text{random} \{ m | m \in \Pi_{o_{i,j,k}} \}$$  (41)

This study establishes the following equipment assignment based on rule priority: minimum conflict time rule, minimum transportation time rule, minimum number of processing heat and random selection rule. The $O_1$, $O_2$ and $O_3$ operating equipment assignment algorithms are described as follows:

Algorithm 3: $O_1$ operating equipment assignment algorithm

**Step 1:** Obtain an operation $o_{i,j,k}$ of the re-scheduling operation set $O_1$, the start time $s^0_{i,j,k}$ and completion time $e^0_{i,j,k}$ of the operation in the initial scheduling plan and the re-scheduling time $t_r$.

**Step 2:** If $k \neq e_{i,j}$, then go to Step 3; else, $z^0_{i,j,k} = 1$, and go to Step 9.

**Step 3:** If $e^0_{o_{i,j,k}} \leq t_r$, or $e^0_{o_{i,j,k}} \leq t_r$ and $e^0_{o_{i,j,k}} > t_r$, then go to Step 4; else, go to Step 5.

**Step 4:** $z^0_{i,j,k} = 1$, $X_{i,j,k} = s^0_{o_{i,j,k}}, Y_{i,j,k} = e^0_{o_{i,j,k}}$, go to Step 10.

**Step 5:** Follow the minimum conflict time rule:

(a) Calculate the start and end times of operation $o_{i,j,k}$ in all equipment: $X_{i,j,k} = Y_{i,j,k-1} + T_{m_i,j,k-1,m}Y_{i,j,k} = X_{i,j,k} + p^0_{i,j,k} (m \in \Pi_{o_{i,j,k}})$.

(b) Calculate $F_m \{ m \in \Pi_{o_{i,j,k}} \}$.

(c) Let $\Pi^1 = \{ \arg\min \{ F_m | m \in \Pi_{o_{i,j,k}} \} \}$.

(d) If $|\Pi^1| = 1$, that is, $\Pi^1$ has only one device, then select the device for operation $o_{i,j,k}$, and go to Step 9; else, go to Step 6.

**Step 6:** Use the shortest transportation time rule from $\Pi^1$:

(a) Let $\Pi^2 = \{ \arg\min \{ T_{m_i,j,k-1,m} | m \in \Pi^1 \} \}$.

(b) If $|\Pi^2| = 1$, that is, $\Pi^2$ has only one device, then select the device for operation $o_{i,j,k}$, and go to Step 9; else, go to Step 7.

**Step 7:** Use the minimum number of equipment rule from $\Pi^2$:

(a) Let $\Pi^3 = \{ \arg\min \{ H_m | m \in \Pi^2 \} \}$.

(b) If $|\Pi^3| = 1$, that is, $\Pi^3$ has only one device, then select the device for operation $o_{i,j,k}$, and go to Step 9; else, go to Step 8.

**Step 8:** When $z^m_{o_{i,j,k}} = 1 (m = \text{random} \{ m | m \in \Pi^3 \})$, go to Step 9.

**Step 9:** $X_{i,j,k} = Y_{i,j,k-1} + T_{m_i,j,k-1,m}Y_{i,j,k}$, and $Y_{i,j,k} = X_{i,j,k} + p^0_{i,j,k}$.

**Step 10:** End.
Algorithm 4: $O_2$ Operating equipment assignment algorithm

Step 1: Obtain an operation $o_{ijk}$ of the re-scheduling operating set $O_2$;

Step 2: $z_{ijk} = 1$;

Step 3: Calculate all the start and end times of operation $o_{ijk}$: $X_{ijk} = Y_{i_{j-1}, k_{j-1}}$, and $Y_{ijk} = X_{ijk} + p_{ijk}$.

Step 4: End.

Algorithm 5: $O_3$ Operating equipment assignment algorithm

Step 1: Obtain an operation $o_{ijk}$ of the re-scheduling operation set $O_3$;

Step 2: The shortest transportation time rule:

(a) Calculate the start and end times of operation $o_{ijk}$ in all equipment: $Y_{ijk} = X_{i,j,k+1} - T_{m_i,j,k+1}$, and $X_{ijk} = Y_{ijk} - p_{ijk}$ ($m \in \Pi_{o_{ijk}}$).

(b) Calculate $F_m (m \in \Pi_{o_{ijk}})$

(c) Let $\Pi^1 = \{ \arg \min \{ F_m | m \in \Pi_{o_{ijk}} \} \}$.

(d) If $|\Pi^1| = 1$, that is, $\Pi^1$ has only one device, then select the device for operation $o_{ijk}$, and go to Step 6; else, go to Step 3.

Step 3: Use the shortest transportation time rule from $\Pi^1$:

(a) Let $\Pi^2 = \{ \arg \min \{ T_{m_i,j,k+1} | m \in \Pi^1 \} \}$.

(b) If $|\Pi^2| = 1$, that is, $\Pi^2$ has only one device, then select the device for operation $o_{ijk}$, and go to Step 6; else, go to Step 4.

Step 4: Use the minimum number of equipment rule from $\Pi^2$:

(a) Let $\Pi^3 = \{ \arg \min \{ H_m | m \in \Pi^2 \} \}$.

(b) If $|\Pi^3| = 1$, that is, $\Pi^3$ has only one device, then select the device for operation $o_{ijk}$, and go to Step 6; else, go to Step 5.

Step 5: Randomly select a device from $\Pi^3$: $z_{ijk} = 1 (m = \text{random}(m_1 | m_1 \in \Pi^3))$, go to Step 6.

Step 6: $Y_{ijk} = X_{i,j,k+1} - T_{m_i,j,k+1}$, and $X_{ijk} = Y_{ijk} - p_{ijk}$.

Step 7: End.

5.2 Ladle matching rule extraction

5.2.1 Minimal generalisation rule learning

Minimal generalisation rule learning method.

The least generalisation (LGG) can directly use the specific facts corresponding to one or more positive examples as initial rules and then gradually generalise the rules to increase their coverage of the sample. The basic idea is as follows:

In a given first-order formula $r_1$ and $r_2$, LGG firstly finds the text of the same predicate and then examines the constant for each position in the text one by one. If the constant in the two words remains unchanged, then it is recorded as $LGG(s,t) = V$. In the future, all the occurrence of $LGG(s,t)$ position with $V$ instead. LGG then ignores $r_1$ and $r_2$, without the text of the common predicate. If the minimum generalisation method contains a predicate that a formula does not have, then the general generalisation method cannot be specialised for that formula. In decarburisation, the ladle matching rule extraction sets the method for learner A. Relative Minimum Generalisation (RLGG) defines the initial rule of example $e$ as $e \leftarrow K$, where $K$ is the sum of all the atoms in the background. The corresponding decarburisation ladle
matching Table 2 data are taken as an example. Let the initial rule be ‘available (1) ← (steel species = AK202204) ∧ (refining path = LR) ∧ ⋯ ∧ (drainage material (West) = forsterite) ∧ (empty ladle weight = 136), ’available(6) ← (steel species = XK437311) ∧ (refining path = LR) ∧ ⋯ ∧ (drainage material (West) = forsterite) and available (x)← (steel species = Y) ∧ (refining path = LR) ∧ ⋯ ∧ (drainage material (West) = forsterite). In decarburisation, the ladle matching rule extraction sets the method for learner B.

5.2.1 Evaluation and selection Decarburisation ladle rule extraction learning assessment and selection of the first choice of experimental evaluation methods are conducted. Then, evaluation learners should be present to measure the standard of generalisation, that is, performance metrics. Finally, a comparison test is also conducted to compare the performance of learners A and B. The steps are shown in Fig. 7.

1. Assessment method: In decarburisation ladle matching rule extraction, the method of leaving the assessment is adopted to avoid decarburisation ladle matching rules extracted through the training data to learn the ladle matching rules showing ‘over-fitting’ and ‘under-fitting’ phenomena. The decarburised ladle selection rules are extracted using random division, and the test evaluation is repeated. Then, the average is taken as the outcome of the assessment results. This work selects 2/3 of the data samples for rule extraction training. One third of the data samples are used to evaluate the test error.

2. Performance metrics: In decalcification ladle matching rule extraction, the definition of the error rate is the number of misclassifications of the total sample size ratio. The accuracy is the correct number of samples classified the proportion of the total sample. In the decimation rules for decarburisation ladle extraction set D, the classification error rate is defined as follows:

$$E(f;D) = \frac{1}{m} \sum_{i=1}^{m} \mathbb{I}(f(x_i) \neq y_i). \quad (42)$$

Accuracy is defined as follows:

$$acc(f;D) = \frac{1}{m} \sum_{i=1}^{m} \mathbb{I}(f(x_i) = y_i) = 1 - E(f;D). \quad (43)$$

In the ladle matching of these two classifications, the ladle matching test samples are classified into real, false positive, true negative and false negative cases according to the real category and the learner prediction category. Let TP, FP, TN and FN represent the corresponding sample number. Then, $TP + FP + TN + FN = \text{total number of samples}$. The ‘confusion matrix’ of the classification results extracted by the decarburisation ladle matching rule is shown in Table 4.

Then, the accuracy rate $P$ and recall rate $R$ are defined as follows:

$$P = \frac{TP}{TP + FP}, \quad (44)$$

$$R = \frac{TP}{TP + FN}. \quad (45)$$

The samples are sorted according to the learner’s prediction of ladle selection, and the rules that learners consider ‘most likely’ to be positive are prescribed, followed by rules that learners consider ‘least likely to be positive. The homeopathic rules are pressed one by one as a positive example to predict and calculate the current recall and accuracy rates. The ‘equilibrium point’ is defined for the rate of recall = recall rate value. The advantages and disadvantages of learners A and B can be compared on the basis of BEP. On this basis, LGG and RLGG are measured based on the definition:

$$F_\beta = \frac{(1 + \beta^2) \times P \times R}{(\beta^2 \times P) + R}. \quad (46)$$

when $\beta = 1$, the accuracy and recall rates are equally important; when $\beta > 1$, the recall rate has a greater impact; when $\beta < 1$, the accuracy rate has a greater impact. In decarbonisation ladle matching, high precision is important to ensure the safety of production. LGG and RLGG can meet the error rate, accuracy and precision requirements.
3. Comparison test: These two classification problems are addressed in ladle matching. Using the set aside method can not only estimate the test error rate of learners A and B but also obtain the difference between the results of LGG and RLGG. Specifically, both are correct, all wrong, and one is the correct number of another wrong sample, as shown in Table 5.

This study assumes that LGG and RLGG have the same behaviour, and \( e_{01} = e_{10} \). Then, \( |e_{01} - e_{10}| \) obeys the normal distribution, the mean is one, the variance is \( e_{01} + e_{10} \).

\[
\chi^2 = \frac{(|e_{01} - e_{10}| - 1)^2}{e_{01} + e_{10}} \quad (47)
\]

The \( \chi^2 \) distribution with 1 degree of freedom is observed. Given a significance of \( \alpha = 0.05 \), one cannot reject the assumption that no difference can be observed in LGG and RLGG performance when the above variable value is less than the threshold value \( \chi^2_0 = 3.8415 \). Otherwise, the assumption that a significant difference exists between LGG and RLGG performance is rejected, and the average error rate of smaller learner performance worsens. The extraction rules for ladle selection involve additional test data to ensure that the learner learning results gradually change from underfitting to overfitting.

### 5.2.2 Ladle selection rules

#### 5.2.2.1 Learner selection

The decarburisation ladle matching rules are extracted using different data to learn. The test data are shown in Table 6.

In Table 6, the deciphering ladle selection rules are applied to extract the amount of test data. The learning results gradually change from underfitting to overfitting. Learner B’s performance is better, and RLGG is more suitable for optional decarburisation ladle when this method is used to obtain matching rules.

### Table 5 Contingency table of learner classification differences

|                | Algorithm B | Algorithm A |
|----------------|-------------|-------------|
|                | True        | False       |
| True           | \( e_{00} \) | \( e_{01} \) |
| False          | \( e_{10} \) | \( e_{11} \) |

#### Table 6 \( \chi^2 \): value of learner

|        | Test data volume |
|--------|------------------|
|        | 120              | 240           | 360           | 600           | 1200          | 2400          |
| A      | 3.5310           | 4.4395        | 4.8323        | 4.1035        | 5.3536        | 5.3604        |
| B      | 3.2132           | 3.8531        | 4.1965        | 3.8542        | 5.1303        | 5.1743        |

### 5.2.2.2 Selection rules for dephosphorisation ladle

(a) Only one online dephosphorisation ladle (R1)
   Rule 1: Only one online dephosphorisation ladle
   \[
   \text{IF } N_z = 1 \text{ THEN } k_1 \text{ for } L_{ij}. \quad (48)
   \]

(b) Two online dephosphorisation ladles (R2)
   Rule 2.1: Two online dephosphorisation ladles are present, and the temperature varies
   \[
   \text{IF } N_z = 2 \text{ and } T(k_1) > T(k_2) \text{ THEN } k_1 \text{ for } L_{ij}. \quad (49)
   \]

   Rule 2.2: Two online dephosphorisation ladles are available, the temperature is the same, and the use time varies.
   \[
   \text{IF } N_z = 2 \text{ and } T(k_1) = T(k_2) \text{ and } L(k_1) > L(k_2) \text{ THEN } k_1 \text{ for } L_{ij} \quad (50)
   \]

(c) No online ladle is available, and a non-online ladle is available (R3).
   Rule 3.1: No online ladle is available, and only one available non-online dephosphorisation ladle is present.
   \[
   \text{IF } N_z = 0 \text{ and } N_f = 1 \text{ THEN } k_1 \text{ for } L_{ij} \quad (51)
   \]

   Rule 3.2: No online ladle is available, and multiple non-online ladles are present, of which only one ladle has the highest temperature.
   \[
   \text{IF } N_z = 0 \text{ and } N_f > 1 \text{ and } T(k_1) > T(k_2) \text{ THEN } k_1 \text{ for } L_{ij} \quad (52)
   \]

   Rule 3.3: No online ladle is available. Nevertheless, multiple off-line ladles are available. More than one ladle have the highest temperature, and only one ladle has the highest use time amongst the ladle with the highest temperature.
   \[
   \text{IF } N_z = 0 \text{ and } N_f > 1 \text{ and } T(k_1) = T(k_2) \text{ and } L(k_1) > L(k_2) \text{ THEN } k_1 \text{ for } L_{ij} \quad (53)
   \]

(d) No dephosphorisation ladle is available (R4)
   Rule 4: No dephosphorisation ladle is available.
where $N_z$ is the number of online dephosphorisation ladles that meet the constraints, $N_f$ is the number of non-online dephosphorisation ladles that meet the constraints, $L_{ij}$ is the amount of heat that currently need to be equipped with dephosphorisation ladles, $T(k)$ is the temperature of the ladle, and $L(k)$ is the life of the ladle;

Rule 5: Ladle selection weight

Each ladle can be expressed as a quaternion $\langle Z(k), T(k), L(k), k \rangle$, where $Z(k)$ is the remaining time of the ladle online ladle, $T(k)$ is the temperature of the ladle, $L(k)$ is the life of the ladle, and $k$ is the serial number of the ladle. The total weight coefficient $W_i$ is defined as follows:

$$W_i = \alpha \cdot (Z(k)) + \beta \cdot (T(k)) + \gamma \cdot (L(k)) + \delta \cdot (k).$$

Take the value based on experience: $\alpha = 1000, \beta = 100, \gamma = 10, \delta = 1$.

5.2.2.3 Selection rules for decarburisation ladle In summary, the field data extraction and ladle matching rules are as follows:

Rule 1: Steel code
Steel has a steel code beginning with KK or XK and needs the ladle whose life is less than 50 and a number of sinks greater than or equal to two and less than 10.

If $Sk_{1,2} = KK$ and $Sk_{1,2} = XK$ THEN $L(k) < 50$ and $2 \leq U_k^k / U_w^k < 10$

Rule 2: The furnace contains LF refining.
Choose a ladle whose used time is not more than 15 and less than 100.

Algorithm 6 Dephosphorisation ladle selection algorithm

Step 1: The heat that need to be equipped with dephosphorisation ladle are sorted from early to late according to the dephosphorisation converter completion time $t_{i,j1}(k_1)$ and the dephosphorisation time set $\Phi = \{L_1, L_2, \ldots, L_N\}$;

Step 2: Initialise the state of all dephosphorisation ladle (ladle temperature $T(k)$, ladle used time $L(k)$ and ladle available time $t_k$); then, initialise $n = 1$;

Step 3: Select a dephosphorisation ladle for the heat according to the corresponding rules;
   a) Only one online ladle, optional dephosphorisation ladle according to R1;
   b) Only two online ladles, optional dephosphorisation ladle according to R2;
   c) No online ladle is present; nonetheless, an off-line ladle is available. Dephosphorisation ladle is optional according to R3;
   d) No online and off-line ladle are available. Dephosphorisation ladle is optional according to R4;
   e) If multiple ladles are available, then select dephosphorisation ladle according to weight coefficient $W_i$;

Step 4: If $n = N$, then go to Step 5; else, $n = n + 1$, and go to Step 3;

Step 5: End.
correspondence between nodes and heat operations is shown in Table 8 according to the scheduling plan at $T_2$ ($T_2=14:21$).

The identification results are obtained by analysing the extent to which the delay time affects the scheduling plan:

1. The breakouts of the caster in heat $L_{23}$ and $L_{24}$ can be simultaneously solved by adjusting the operating time.
2. Heat $L_{24}$ and $L_{25}$ have a heat operation conflict on the converter equipment. The operating conflict can be simultaneously resolved by adjusting the operation time of heat $L_{24}$ and $L_{25}$ on the converter equipment.
3. The operating conflict between heat $L_{24}$ and $L_{25}$ on the continuous caster can be simultaneously resolved by adjusting the operation time of heat $L_{24}$ and $L_{25}$ on the converter, refining furnace or continuous caster. According to the on-site manual scheduling method, all heat operating adjustments in the scheduling plan will include the reselection of processing equipment and the adjustment of the processing start and end times of the heat operation. The method in this study can solve this problem by adjusting the operating time of some heat; it ensures the continuity and stability of the scheduling plan and is beneficial to the stable and smooth production.

The rescheduling software system is designed and developed on the basis of the rescheduling algorithm proposed. The object oriented idea and modular reuse technology are adopted. This mechanism consists of real-time data acquisition, charge tracking, charge query, machine assignment, starting and completion time adjustment based on the heuristic method, starting and completion

6 Application examples

Based on the application analysis of a steelmaking plant in Shanghai China, the plant often experienced delays in the start-up time of molten steel on the converter equipment, resulting in scheduling plans due to continuous casting breakout or furnace operating conflicts. At present, the factory scheduling is mainly based on manual adjustment. The selection of the adjustment method is based on manual experience simply by delaying the start time within 5 min, between 5 and 10 min and more than 10 min to classify the time: (1) when the delay is less than 5 min, the scheduling plan will not be adjusted; (2) when the start time is delayed between 5 and 10 min, the processing start and end times are adjusted; and (3) when the time delay is greater than 10 min, the device is reselected. Manual adjustment leads to large fluctuations in production, which affects the production stability and continuity.

This study takes the actual SCC production ladle scheduling problem of this enterprise as an example to illustrate the application of this method and manual adjustment method. Figure 8 shows the pouring order information at time $t_1$: cast on 4CC, $\Omega_1 = \{L_{11}, L_{12}, L_{13}, L_{14}, L_{15}, L_{16}, L_{17}\}$; cast 2 on 5CC, $\Omega_2 = \{L_{21}, L_{22}, L_{23}, L_{24}, L_{25}, L_{26}, L_{27}\}$; and cast 3 on 6CC, $\Omega_3 = \{L_{31}, L_{32}, L_{33}, L_{34}, L_{35}, L_{36}, L_{37}\}$. The processing time of the heat on the continuous caster is shown in Table 7.

In Fig. 9, the operation of heat $L_{24}$ on the converter 5LD $\alpha_{241}$ starts processing, that is, $s_{241}^* = 14 : 21$. The correspondence between nodes and heat operations is shown in Table 8 according to the scheduling plan at $T_2$ ($T_2=14:21$).

The identification results are obtained by analysing the extent to which the delay time affects the scheduling plan: (1) The breakouts of the caster in heat $L_{23}$ and $L_{24}$ can be simultaneously solved by adjusting the operating time. (2) Heat $L_{24}$ and $L_{25}$ have a heat operation conflict on the converter equipment. The operating conflict can be simultaneously resolved by adjusting the operation time of heat $L_{24}$ and $L_{25}$ on the converter equipment. (3) The operating conflict between heat $L_{24}$ and $L_{25}$ on the continuous caster can be simultaneously resolved by adjusting the operation time of heat $L_{24}$ and $L_{25}$ on the converter, refining furnace or continuous caster. According to the on-site manual scheduling method, all heat operating adjustments in the scheduling plan will include the reselection of processing equipment and the adjustment of the processing start and end times of the heat operation. The method in this study can solve this problem by adjusting the operating time of some heat; it ensures the continuity and stability of the scheduling plan and is beneficial to the stable and smooth production.
time adjustment based on the linear programming, human–computer interaction adjustment, performance evaluation of the rescheduling algorithm, process data management, equipment environment configuration and user management.

According to statistics, the average time for preparing a ladle scheduling plan compared with on-site manual ladle scheduling using the method proposed in this work is 3.4 s, which is far less than the average manual preparation time of 30 s. The number of online ladles is reduced from 23 to 19, and the number of daily ladle maintenance is reduced from 17 to 12 times. The time hit rate of heat (the proportion of heat that is strictly processed according to the plan) has been increased from 61 to 65% compared with manual preparation. The average daily waiting time is reduced from 234 to 166 min, and the average daily load ratio is increased from 50.44% to 55.16%. The number of charges increases from 1980 to 2040 on average within 30 days, there greatly improving the production efficiency. The rescheduling time is shortened from 1 min to less than 10 s, which thus improving the rescheduling efficiency. The selection method proposed in this study can smoothen the steelmaking–refining–continuous casting production.

**Table 7** Processing time on the continuous castors

| Heat operation | \(a_{13} \) | \(a_{123} \) | \(a_{133} \) | \(a_{143} \) | \(a_{153} \) | \(a_{163} \) | \(a_{173} \) | \(a_{213} \) | \(a_{223} \) | \(a_{233} \) | \(a_{243} \) |
|----------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| Minimum processing time (minutes) | 45 | 45 | 45 | 50 | 55 | 45 | 40 | 45 | 45 | 50 | 45 |
| Standard processing time (minutes) | 48 | 48 | 49 | 58 | 60 | 46 | 42 | 46 | 46 | 50 | 50 |
| Maximum processing time (minutes) | 60 | 60 | 61 | 70 | 75 | 60 | 60 | 60 | 60 | 65 | 65 |
| Heat operation | \(a_{253} \) | \(a_{263} \) | \(a_{273} \) | \(a_{283} \) | \(a_{313} \) | \(a_{323} \) | \(a_{333} \) | \(a_{343} \) | \(a_{353} \) | \(a_{363} \) |
| Minimum processing time (minutes) | 45 | 50 | 45 | 45 | 60 | 60 | 60 | 60 | 60 | 60 |
| Standard processing time (minutes) | 50 | 55 | 52 | 54 | 74 | 74 | 76 | 76 | 76 | 77 |
| Maximum processing time (minutes) | 65 | 70 | 67 | 70 | 85 | 85 | 85 | 85 | 85 | 85 |
decision charges and long preparation time but also long waiting time and low rescheduling efficiency.

The scheduling of SCC production takes the production process routes and the processing time of charges as fixed constants. The production objectives are as follows: (i) each cast should timely start on the caster; (ii) a set of charges within the same cast should be casted on the same caster; and (iii) the processing of adjacent charges should not conflict on the same machine.

In SCC production processes, the starting time delay frequently occurs, which may lead to casting break or processing

![Fig. 9 Scheduling plan at time $t_2$](image)

### Table 8 Correspondence between nodes and operations

| Node | Operation | Node | Operation | Node | Operation |
|------|-----------|------|-----------|------|-----------|
| 1    | $o_{151}$ | 2    | $k_{161}$ | 3    | $o_{161}$ |
| 4    | $o_{171}$ | 5    | $o_{241}$ | 6    | $k_{251}$ |
| 7    | $o_{251}$ | 8    | $o_{251}$ | 9    | $o_{261}$ |
| 10   | $o_{261}$ | 11   | $k_{271}$ | 12   | $o_{271}$ |
| 13   | $k_{281}$ | 14   | $o_{281}$ | 15   | $o_{131}$ |
| 16   | $o_{131}$ | 17   | $k_{341}$ | 18   | $o_{341}$ |
| 19   | $o_{341}$ | 20   | $k_{351}$ | 21   | $o_{351}$ |
| 22   | $o_{351}$ | 23   | $k_{361}$ | 24   | $o_{361}$ |
| 25   | $o_{361}$ | 26   | $k_{371}$ | 27   | $o_{371}$ |
| 28   | $o_{371}$ | 29   | $k_{381}$ | 30   | $o_{381}$ |
| 31   | $o_{381}$ | 32   | $k_{391}$ | 33   | $o_{391}$ |
| 34   | $o_{391}$ | 35   | $k_{401}$ | 36   | $o_{401}$ |

7 Conclusion

The rescheduling optimization of SCC production aims at minimizing the waiting time of all charges. This task leads to hundreds of conflicting constraint equations. The above-mentioned conflicting constraint equations are difficult to simultaneously satisfy using the optimization algorithms that adopt mathematical programming or evolutionary computation. Accordingly, this task can only rely on experienced scheduling practitioners to make a rescheduling plan. However, the manual rescheduling scheme has not only less decision charges and long preparation time but also long waiting time and low rescheduling efficiency.

The scheduling of SCC production takes the production process routes and the processing time of charges as fixed constants. The production objectives are as follows: (i) each cast should timely start on the caster; (ii) a set of charges within the same cast should be casted on the same caster; and (iii) the processing of adjacent charges should not conflict on the same machine.

In SCC production processes, the starting time delay frequently occurs, which may lead to casting break or processing
In view of the low efficiency of the current manual-made ladle scheduling, the manual selection of a ladle wastes resources and easily lead to excessive redundancy in SCC production. This work comprehensively considers the process constraints and the limitation factors to address the ladle re-scheduling problem. In comparison with previous studies, this work simultaneously considers the SCC production equipment scheduling problem and the ladle selection problem. Moreover, this work proposes a ladle re-scheduling method, which can effectively avoid the effect of disturbances during production. The simulation experiment of the SCC production rescheduling algorithm is carried out by using practical data. The simulation results demonstrate the effectiveness of the proposed rescheduling algorithm.

Industrial verification was carried out based on the actual data from a steel company in Shanghai, China. The ladle re-scheduling method proposed in this work can meet the requirements of the process for the ladle and reduce the production delay caused by unreasonable scheduling. The results showed that the production efficiency of steelmaking–refining–continuous casting was improved. The production efficiency and the economic benefits of the enterprise are better compared with the previous manual establishment of on-site dispatchers.

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Author contribution Wei Liu: Developed or designed the methodology; created the models; carried out the programming; developed the software; designed the computer programs; conducted the implementation of the computer code and supporting algorithms; tested the existing code components; and applied the statistical, mathematical, computational or other formal techniques to analyse or synthesise the study data. Xinfu Pang: Conducted the research and investigation; performed the experiments or data/evidence collection; and carried out management activities of annotating (produce metadata), scrubbing data and maintaining research data (including software code, where it is necessary for interpreting the data itself) for initial and future use. Haibo Li: Prepared, created and/or presented the published work, specifically visualisation/data presentation; performed oversight function; and headed the research activity planning and execution, including mentorship external to the core team. Liangliang Sun: Managed and coordinated the research activity planning and execution; helped in acquiring the financial support for the project leading to this publication.

Declarations

Consent to participate Not applicable.

Consent for publication Not applicable.

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