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Scheduling Model for the Practical Steelmaking-continuous Casting Production and Heuristic Algorithm Based on the Optimization of "Furnace-caster Matching" Mode

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Considering the "furnace-caster matching" modes, this paper focuses on the scheduling problems from practical steelmaking-continuous casting production lacking refining span. Aiming at the improvement on quality and output of steel products, a mathematical model is established with multi-objective optimization including the minimum earliness/tardiness of starting cast times, the shortest waiting times of heats among different processes and the shortest idle times of converters. A heuristic algorithm based on the optimization of "furnace-caster matching" mode is developed to solve this model, which involves two procedures of device assignment and conflict elimination. Through the detailed analysis on workshop layout and production rhythm, four classes of matching modes of "refining furnace-caster" are proposed to perform the assignments of refining furnaces. The assignments of converters rely on three categories of greedy strategies in terms of minimizing conflictions among heats. A rough scheduling solution with some possible conflicts among heats is obtained through combining "furnace-caster matching" modes and greedy strategies. Then applying the linear programming method to eliminate the conflicts and generate the final solution. Based on the proposed algorithm and the improved genetic algorithms, simulation experiments are carried out by introducing actual production plans as instances. The results indicate that heuristic algorithm based on the optimization of "furnace-caster matching" mode is the right candidate owing to its acceptable scheduling solutions with the better process matching relations and the highlighted performances under crane constraint. Currently, the proposed model and algorithm have been successfully used in a large converter steel plant in China.

KEY WORDS: steelmaking-continuous casting; workshop layout; scheduling model; heuristic algorithm; furnace-caster matching.

1. Introduction

Nowadays, the steel industry still represents one of the major industries in the world economy, and China's steel output reaches up to 0.928 billion tons in 2018, which accounts for more than 50 percent of the total output in world. Indeed, the higher output can't be separated from the advances on operation control in steel manufacturing. Owing to the characteristics of high-temperature (> 1 600°C), multi-process, quasi-continuation along with various complex physical and chemical reactions among gas-liquid-solid multiphase, the steelmaking-continuous casting process (SMCC) is regarded as the core section in steel manufacturing,[1] and its operation control faces more challenges in comparison to ironmaking and rolling. With the rapid development of "Intelligent Manufacturing" in multiple fields at present,[2] such as the automobile manufacturing[3] and the sophisticated equipment assembly,[4] the steelmaking plants also need a transition from extensive form to intensive form, and the fine control in SMCC is the key aspect to achieve the intelligent production of steelmaking.[5] Currently, various technologies concerning single-process control have been significantly improved,[6,7] such as the automation and visualization of steelmaking process[8,9] as well as the advanced tundish technology for casting clean steel.[10] While the control of multi-process coordinated operation still mainly depends on the artificial expertise, which limits the intellectualization evolution of SMCC.

As the crucial part of multi-process coordinated operation in SMCC, the scheduling problems have been addressed by many scholars in recent years. At present, the most popular approaches involves operations research algorithms, heuristic algorithms, and intelligence optimization algorithms.[11] Mao *et al.*[12] presented a Lagrangian relaxation (LR) approach to solve the mixed-integer programming (MIP) problem derived from steelmaking-continuous casting process. Yu *et al.*[13] offered several heuristic approaches referring to scheduling sequence and facility assignment to solve the scheduling problems of multi-stage refining. Tang *et al.*[14] proposed a differential evolution algorithm with an improved mutation

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strategy used to raise the solving efficiency.

Although plenty of works have been performed about the scheduling in SMCC, most studies focus on the improvement of solving algorithms to pursue the higher computational efficiency and the better objective results. Since the steelmaking production is restricted by the strict constraints on temperature and composition of molten steel, waiting times among different processes, etc, the scheduling in SMCC is more difficult than that in discrete manufacturing industries.[15] Thus, more consideration should be given on actual production modes and process rules in SMCC to raise the validity of scheduling models and solving algorithms. Liu *et al.*[16] summarized the operation principles and control strategies for steelmaking system and indicated the "furnace-caster matching" was the primary principle to keep high-efficiency operation in SMCC. Wang *et al.*[17] presented the static scheduling models by introducing the rules of converter-caster matching and designed the dynamic scheduling approaches based on the flexibilities of refining furnace in processing time. Gu *et al.*[18] proposed the "quasi-laminar flow" production pattern for the complex production in Tangshan Iron and Steel Co., Ltd. on account of process matching in steelmaking-continuous casting-rolling process. Yuan[19] built a constraint satisfaction model with the optimization of furnace-caster matching degree and used an improved NSGA-II algorithm with adaptive grid selection strategy to solve this model. Indeed, the workshop layout and production rhythm should be paid more attention to determine the correct "furnace-caster matching" relations. In particular, the ideal matching mode of "a certain furnace to a certain caster" is difficult to achieve if the processing time of converter (refining furnace) is larger than that of caster. Such case, of course, is universal in steelmaking production, whose scheduling is still a complex problem.

Due to the limit of refining technologies and the need of more common steel, most early steel plants are built with less consideration on the introduction of refining process as well as the design of refining span. Currently, multiple refining methods are gradually used in these plants due to the requirement of high quality steel as well as the improvement of refining technologies. Obviously, the addition of refining stations causes the operations of tapping, refining and casting all processed in the limited space with multi-process and multi-device. Hence, the operation of mass flow (mainly denoted as molten steel, casting blank and carbon-based gases) in SMCC is extremely complex with the production orders of multi-grade, small-batch and multi-specification yet. Therefore, there is a practical significance to study the scheduling problems in this type of steel plants, and especially the research on "furnace-caster matching" mode is more important to avoid excessive conflicts among cranes. A large converter plant lacking refining span in China is selected as the research object in this paper. According to production scenario, a scheduling model for SMCC is established with the minimization of the deviation on starting cast times compared to the planned, the waiting times of heats among different processes as well as the idle times of converters. A heuristic algorithm based on the optimization of "furnace-caster matching" mode is proposed. Finally, simulation experiments are carried out with actual production plans. In addition, the improved genetic algorithms are also applied as the comparisons. The rest of this paper is organized as follows. Section 2 describes the production process of SMCC and proposes the scheduling model; Section 3 introduces the heuristic algorithm based on the optimization of "furnace-caster matching" mode; Simulation experiments and result analysis are presented in Section 4; Finally, the conclusions are given in Section 5.

2. Problem Description and Mathematical Model

Modeling the scheduling problem is a complicated task. The detailed procedures are as follows: (1) analyze problem characteristics through on-site survey; (2) determine optimization objectives and constraints based on production characteristics in SMCC; (3) formulate a mathematical model in terms of objectives and constraints. This section will give a detailed description for the scheduling problem of SMCC in an actual steel plant and establish the mathematical model.

2.1. Process Analysis of SMCC

SMCC in the studied steel plant mainly includes four stages: converter (BOF), ladle furnace refining (LF), vacuum refining (RH) and continuous casting (CCM). The workshop layout and device configuration are respectively shown in **Fig. 1** and **Table 1**.

As shown in Fig. 1 and Table 1, the SMCC presents an extremely complex layout where many devices are located in tapping (casting) span due to the lack of refining span. Thus, the control of mass flow operation in the studied plant is much harder compared to the steel plants with refining span. Furthermore, the production scheduling in the studied plant and most other steel plants still depends on artificial experience. The low efficiency on production organization is inevitable along with the heavy workload for planners, which further blocks the raise of slab output and the efficient utilization of single-process models. Therefore, it is necessary and meaningful to develop scheduling model for such complex steelmaking production.

On the basis of device configurations and production orders, the process routes of steel products in the studied plant can be divided into the following three classes: a) BOF→LF→CCM, b) BOF→RH→CCM, c) BOF→LF→RH→CCM. The steel grades produced in each process route as well as the corresponding CCMs are listed in **Table 2**, where the statistical results come from the actual production data from June, 2018 to September, 2018. The data reported in Table 2 reveals that the process routes of BOF→LF→CCM and BOF→LF→RH→CCM are frequently applied in actual production. The castings of high-quality steel processed in LF and RH successively are all carried out in No. 4 CCM. **Table 3** summarizes the statistical results on processing times of each process. Since the single-process control in the studied plant has achieved an advanced level, the large fluctuation on processing times of BOF, LF and RH is mainly resulted from the mismatching of production rhythm among different processes. For casting time of CCM, its fluctuation is due to the diversity of section size.

2.2. Problem Description for SMCC Scheduling

According to previous study,[20] the scheduling problem in SMCC is simplified as a hybrid flow-shop scheduling problem (HFSP) with parallel machines in each stage. However, considering the requirement of casting continuously and the quality of molten steel in whole process, the scheduling in SMCC is more complicated than that in common HFSP. Before modeling, the critical step is to generalize

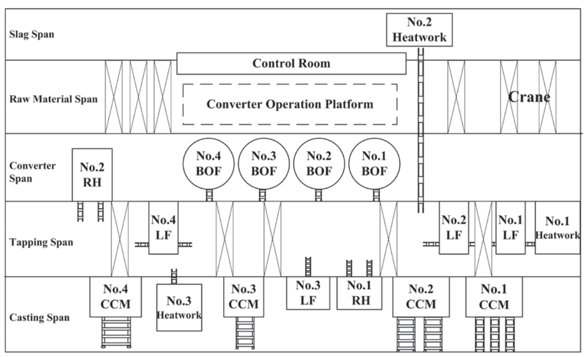

Fig. 1. Workshop layout in SMCC.

Table 1. Device configuration in SMCC.

Device Type	Amount	Specification	Attribute
BOF	4	4 × 130[a)]	Top-bottom combined blowing
LF	4	4 × 130	No. 1, No. 2, No. 4: Double-station No. 3: Single-station
RH	2	2 × 130	No. 1, No. 2: Double-station:
Special-shaped CCM	1	(550/750/1 024) × (370/390/440) × 90[b)]	No. 1: Three machines to three streams
Medium-thick slab CCM	2	175 × (980–1 360)	No. 2: Double machines to double streams No. 3: Single machine to single stream
Wide-thick slab CCM	1	(200/250/300) × (1 500–2 500)	No. 4: Single machine to single stream

[a)]: Nominal capacity with unit of ton; [b)]: Section size with unit of mm^3 (mm^2).

the scheduling rules, so as to identify the correct objectives and constraints. The detailed scheduling rules in SMCC are listed as follows:

(1) Heats in a cast must be casted continuously in the same CCM, and the upper bound of heat number in a cast can't exceed the lifetime of tundish;

(2) Since the strict demand on temperature and chemical component of molten steel, the waiting time, especially before casting, must be controlled within a limited time;

(3) The preparation time of 120 min is necessary between adjacent casts in the same CCM to exchange tundish and adjust mold specification;

(4) In order to coordinate the operation rhythm between BOFs and CCMs, it is allowable to adjust the refining time within a limited range;

(5) To avoid casting failure, the casting speed also can be changed within the permissible range, while it is not a common method due to the bad effect on quality of blank;

(6) For adjacent heats in the same device, only if the operation of the forward one finished, the backward one can be processed;

(7) Only has the operation of a heat been completed in current device, it can be transported to next device to be processed according to process route;

The rules of (1), (2), (3), (6) and (7) are strict constraints, while the rules of (4) and (5) are flexible constraints generally used in dynamic scheduling. Since dynamic scheduling is not discussed in this paper, the rules of (4) and (5) will not be considered.

Besides the determination of constraints, the known parameters and necessary hypotheses also should be illustrated as follows:

(1) Except for CCM stage, the devices in the same stage are identical, and the total weight of molten steel for casting is stable at approximately 130 t.

(2) The production plans for scheduling are known in advance and include the following details: the cast number, the corresponding CCMs of each cast as well as their starting times, completion times and section sizes; the heat number in each cast and the corresponding process routes.

(3) The transportation capacity of cranes and ladles are enough to meet the scheduling demands.

2.3. Definition of Parameter and Variable

The parameters and decision variables are defined as follows:

2.3.1. Index and Parameter

I — Heat set, $|I|$ indicates the total heat number in production plans for scheduling;

i — Heat index, $i \in I$;

N — Cast set, $|N|$ indicates the total cast number in production plans for scheduling;

n — Cast index, $n \in N$;

I_n — Heat set in cast n, $I_1 \cup I_2 \cup I_3 \cup \ldots \cup I_{|N|} = I$ and $I_1 \cap I_2 \cap I_3 \cap \ldots \cap I_{|N|} = \varnothing$;

Table 2. Process routes and corresponding casters for main steel grades.

Process Route	Steel Grade	Caster	Sample Size
BOF–LF–CCM	Q235B, Q345B, SPHC, AH36, *etc.*	No. 1 CCM/ No. 2 CCM No. 3 CCM	10 263
BOF–RH–CCM	DC04 (DC05)	No. 2 CCM	82
BOF–LF–RH–CCM	High Strength Structural Steel and Shipbuilding Steel, *etc.* such as Q550D and NVA36	No. 4 CCM	1 448

Table 3. Statistical results of processing times in each process.

Process and Device		Min/ min	Max/ min	Mean/ min	Mode/ min	Median/ min	Sample Size
BOF		35	48	40	40	39.5	3 282
LF	Heating	23	37	31	30	31	2 701
	Soft Blowing	8	16	12	12	12	2 701
RH		11	38	31	30	33	627
No. 1 CCM		41	55	45	45	44	1 619
No. 2 CCM		27	44	35	35	36	1 407
No. 3 CCM		51	70	55	55	56	1 412
No. 4 CCM		25	58	35	34	36	1 127

$FH(n)$ — The first heat in cast n;

J — Process set in SMCC, J^* is the process set without the process of CCM;

J_i — Process set of heat i processed sequentially, $|J_i|$ is the total process number in J_i;

J_i^* —Process set of heat i without the process of CCM, $|J_i^*|$ is the total process number in J_i^*;

j — Process index, $j \in J$;

M_j — Device set in process j, $|M_j|$ is the total device number in process j;

k — Device index, $k \in M_j$, k_{ij} indicates the assigned device of heat i in process j;

$T_{i,j,k_1}^{i,j+1,k_2}$ — Transportation time of heat i from device k_1 in process j to device k_2 in process $(j+1)$;

P_{ij} — Processing time of heat i in process j, $i \in I$, $j \in J_i$, P_{ij} is determined by mode in Table 3 because of the lower reliability of mean;

T_n — Starting time of cast n at CCM, and rank all casts in N as ascending order of T_n, that is $T_1 < T_2 < \ldots < T_{|N|-1} < T_{|N|}$, and they are determined by the manual in terms of the requirement of current production plans as well as the performance of previous production plans;

t_{ijk}^*, c_{ijk}^* — Expected starting time and expected completion time of heat i on device k in process j, $i \in I$, $j \in J_i$,

$k \in M_j$, and $t^*_{FH(n),|J_{FH(n)}|,k_{FH(n),|J_{FH(n)}|}} = T_n$, which can be simplified as $t^*_{FH(n),|J_{FH(n)}|} = T_n$ due to the known CCMs for each cast in advance;

$C1_n$, $C2_n$, $C3_i$, $C4_k$ — Penalty coefficients for the earliness/tardiness of starting cast times, the waiting times of heats among different processes and the idle times of BOFs;

U — A very large positive number.

2.3.2. Decision Variable

x_{ijk} — Binary variable. If heat i is assigned to device k in process j, $x_{ijk}=1$, otherwise, $x_{ijk}=0$, $i \in I$, $j \in J_i^*$, $k \in M_j$;

$y_{i_1 i_2 j}$ — Binary variable. If heat i_1 precedes heat i_2 in process j, $y_{i_1 i_2 j}=1$, otherwise, $y_{i_1 i_2 j}=0$, $i_1 \in I$, $i_2 \in I$, $j \in J^*_{i_1} \cap J^*_{i_2}$;

E_{jk} — Set of heats assigned to device k in process j, $E = \bigcup_{k \in \{1,2,\ldots,|M_j|\}} E_{jk}$, $|E_{jk}|$ is the heat number in E_{jk}, $j \in J^*$, $k \in M_j$;

$i_{E_{jk}}$ — Index of heats assigned to device k in process j, $i_{E_{jk}} \in E_{jk}$, $j \in J^*$, $k \in M_j$;

t_{ijk}, c_{ijk} — Continuous variables representing the starting time and completion time of heat i on device k in process j, $i \in I$, $j \in J_i$, $k \in M_j$;

2.4. Mathematical Model for SMCC Scheduling

Through the analysis on actual production situation in the studied plant, the restrictive factors for improvement on quality and output of steel products mainly involve the long waiting times of heats among different processes, the frequent adjustments on starting cast times as well as the poor converter arrangement. In particular, the long waiting time before casting may lead to casting failure as a result of the larger temperature drop of molten steel. The tardiness on starting cast time may cause failure for on-time delivery of blanks to rolling process. The longer idle times of BOFs will lengthen smelting time to keep the tapping temperature and further decrease the production efficiency. Therefore, the optimal objectives in this model are to minimize the total earliness/tardiness of starting cast times, the total waiting times of heats among different processes and the total idle times of BOFs. The detailed mathematical expressions are formulated as follows along with the requisite constraints.

$$f_1 = \min \sum_{n=1}^{|N|} \Big(C1_n \cdot \max(0, t^*_{FH(n),|J_{FH(n)}|} - t_{FH(n),|J_{FH(n)}|}) + C2_n \cdot \max(0, t_{FH(n),|J_{FH(n)}|} - t^*_{FH(n),|J_{FH(n)}|}) \Big) \quad \ldots (1)$$

$$f_2 = \min \sum_{i=1}^{|I|} \sum_{j=1}^{|J_i^*|} C3_i \cdot \left(t_{i,j+1,k_{i,j+1}} - c_{ijk_{ij}} - T^{i,j+1,k_{i,j+1}}_{i,j,k_{ij}} \right) \quad \ldots (2)$$

$$f_3 = \min \sum_{k=1}^{|M_1|} \sum_{i_{E_{1k}}=1}^{|E_{1k}|-1} C4_k \cdot \left(t_{i_{E_{1k}}+1,1,k} - c_{i_{E_{1k}},1,k} \right) \quad \ldots (3)$$

s.t.

$$\sum_{k=1}^{|M_j|} x_{ijk} = 1, \forall i \in I, j \in J_i^* \quad \ldots (4)$$

$$t_{i_2 jk} - c_{i_1 jk} + \left(3 - x_{i_1 jk} - x_{i_2 jk} - y_{i_1 i_2 j}\right) \cdot \mathrm{U} \geq 0, \forall i_1, i_2 \in I \wedge i_1 \neq i_2, j \in J^*_{i_1} \cap J^*_{i_2}, k \in M_j \quad \ldots (5)$$

$$t_{i+1,|J_{i+1}|} = c_{i,|J_i|}, \forall i, i+1 \in I_n, n \in N \quad \ldots (6)$$

$$t_{i,j+1,k_2} - T^{i,j+1,k_2}_{i,j,k_1} + \left(2 - x_{ijk_1} - x_{i,j+1,k_2}\right) \cdot \mathrm{U} \geq c_{i,j,k_1}, \forall i \in I, j \in J_i^*, k_1 \in M_j, k_2 \in M_{j+1} \quad \ldots (7)$$

$$c_{ijk_{ij}} = t_{ijk_{ij}} + P_{ij}, \forall i \in I, j \in J_i \quad \ldots (8)$$

$$\prod_{i_{E_{jk}}=1}^{|E_{jk}|} x_{i_{E_{jk}},j,k} = 1, \forall j \in J^*, k \in M_j \quad \ldots (9)$$

$$y_{i_1 i_2 j} + y_{i_2 i_1 j} = 1, \forall i_1, i_2 \in I \wedge i_1 \neq i_2, j \in J^*_{i_1} \cap J^*_{i_2} \quad \ldots (10)$$

$$x_{ijk} \in \{0,1\}, \forall i \in I, j \in J_i^*, k \in M_j \quad \ldots (11)$$

$$y_{i_1 i_2 j} \in \{0,1\}, \forall i_1, i_2 \in I \wedge i_1 \neq i_2, j \in J^*_{i_1} \cap J^*_{i_2} \quad \ldots (12)$$

$$t_{ijk} \geq 0, \forall i \in I, j \in J_i, k \in M_j \quad \ldots (13)$$

Objective functions (1)–(3) are to minimize the total earliness/tardiness of starting cast times, the total waiting times of heats among different processes and the total idle times of BOFs respectively. Constraint (4) ensures that each heat can be only operated by one device in a process; Constraint (5) reveals only the operation of current heat completed, the next heat can be processed in the same device; Constraint (6) shows the restriction of casting continuously in CCM process; Constraint (7) indicates a heat can start its operation at a process if it has been transported to this process after completing its operation at previous process; Constraint (8) claims the operation of any heat in each process is not allowed to be interrupted; Constraints of (9)–(13) restrict the values or ranges of decision variables.

3. Heuristic Algorithm Based on "Furnace-Caster Matching" Optimizing

The scheduling model for SMCC is a mixed integer programming problem. The exact algorithms such as Lagrange algorithm have a low efficiency to solve such large scale problems.[12,21] The solving mechanisms of intelligence optimization algorithms such as genetic algorithm (GA), are originated from simulating biological evolution or population behavior. For the steel plants with complex layout, the optimization of production modes in SMCC plays an important role in solving the scheduling problems.[5] While the various production modes are hardly introduced in intelligence optimization algorithms. Indeed, heuristic algorithms can be treated as the potential candidate to solve the practical scheduling problems as it can highlight the detailed production modes. The solving of the proposed heuristic algorithm in this paper mainly includes two procedures. Firstly, assign devices to all heats and generate a rough schedule solution. Secondly, eliminate conflictions between heats in rough scheduling by the linear programming approach, and then obtain the final scheduling scheme.

3.1. Device Assignment Strategy

To avoid the frequent cross-supply of molten steel and achieve the orderly running of mass flow, the ideal operation in SMCC is the "laminar flow" mode that exhibits the matching relationships of fixed and non-crossed among converters, refining furnaces and casters,[1,22] as shown in **Fig. 2**. Obviously, it is easy to perform the task of device assignment in the "laminar flow" mode. As a result of the complex layout without refining span as well as variable casting times in the studied steel plant, it is hard to establish the expected matching relations among different processes, which raises the difficulty of device assignment in SMCC. So it is great significant to study the operation rules of mass flow in such a complex SMCC and determine the matching modes among processes under different production cases to further offer the guidance for device assignment.

3.1.1. Assignment of Refining Furnaces Based on "Furnace-Caster Matching"

To further analyze the refining configuration, LF with double-station can be regarded as two single stages of heating refining and soft blowing, whose standard processing times are respectively 30 min and 12 min. Since the processing time of RH is commonly set as 30 min, the matching relations between RHs and LFs can be built where No. 3 LF

(No. 4 LF) corresponds to No. 1 RH (No. 2 RH) in terms of the closest distance between them. Similarly, the matching between LFs (RHs) and CCMs also can be realized when the casting times of CCMs are not less than 30 min. Due to the casting time of No. 2 CCM (No. 4 CCM) less than 30 min under some section sizes, the expected matching relations couldn't be completely achieved. So the "LF (RH)–CCM matching" modes are determined according to whether the casting time of No. 2 CCM (No. 4 CCM) is less than 30 min or not. Owing to the total production capacity of No. 1–No. 4 CCMs obviously larger than that of No. 1–No. 4 BOFs by capacity calculation based on Table 3, it is correct to apply the production scheme of three sets of CCMs operating simultaneously, and the matching modes between LFs (RHs) and CCMs are illustrated in detail as the following four cases.

(1) No. 1 CCM Out of Operation

When No. 1 CCM is out of operation, both No. 2 CCM and No. 4 CCM are in the state of working. Under this case, the "LF (RH)–CCM matching" modes are grouped into four categories on the basis of the casting times of No. 2 CCM (T_{CCM2}) and No. 4 CCM (T_{CCM4}), which are shown as **Fig. 3**. The "laminar flow" mode can be realized only if T_{CCM2} and T_{CCM4} are not less than 30 min at the same time. Otherwise, the cross-supply of molten steel may occur frequently. Even though the matching modes become complicated, the cross-supply modes also can be predicted just as displayed in Fig. 3(d). When only T_{CCM4} is less than 30 min, the corresponding LF for No. 2 (3) CCM will shift from No. 2 (3) LF to No. 1 (2) LF, and No. 3 LF will serve No. 4 CCM. The purpose of changing matching relations is to pursue the minimum on transportation distance of cranes among different processes, and the scheduling of cranes will become a big challenge if No. 1 LF offers molten steel for No. 4 CCM.

(2) No. 2 CCM Out of Operation

When No. 2 CCM is unavailable, the operation rhythm in continuous-casting stage will be relaxed in comparison with the case of No. 1 CCM out of operation. The matching modes of "LF (RH)–CCM" is just affected by T_{CCM4} and exhibited in **Fig. 4**. Since the casting time of No. 1 CCM is more than 40 min under any section sizes, the fixed matching can be achieved between No. 1 CCM and a certain LF (BOF). With the objective of the shortest transportation distance among devices, No. 1 BOF (Not depicted in Fig. 4) and No. 1 LF are right candidates to establish a special production line with No. 1 CCM. Similar as the case in Fig. 3(c), the corresponding relations between LFs and CCMs also should be adjusted if $T_{CCM4} < 30$ min, in which No. 2 LF operates online.

(3) No. 3 CCM Out of Operation

With respect to the case of No. 3 CCM unavailable, the risk of casting failure is high due to the faster casting rhythm when three sets of CCMs of No. 1, No. 2 and No. 4 operate simultaneously. Under such circumstances, the detailed "LF (RH)–CCM matching" modes is exhibited in **Fig. 5**. Due to the processing time of No. 1 BOF closed to the casting time of No. 1 CCM, the amount of molten steel delivered from No. 1 LF (No. 1 BOF) to No. 2 CCM is limited in the case shown as Fig. 5(d). Moreover, there is also a large challenge for No. 3 LF to alternately supply molten steel for No. 2 CCM and No. 4 CCM because of their various casting times.

(4) No. 4 CCM Out of Operation

If No. 4 CCM is in the state of downtime, two sets of RHs also stop working. It is clear that each LF corresponds to the unique CCM whether T_{CCM2} exceeds 30 min or not, as shown in **Fig. 6**. Thus, the operation control of mass flow will be easier than other cases. In consideration of the maximization on slab output, the third case of No. 3 CCM out of operation is the more popular production mode.

The basic idea for device assignment is to select the processing devices for each heat as the inverted sequence from CCM to BOF,[13] and thus the assignments of both LF and RH are carried out in terms of the analysis on above matching modes. In particular, which CCM is not working is determined before scheduling based on the details of cur-

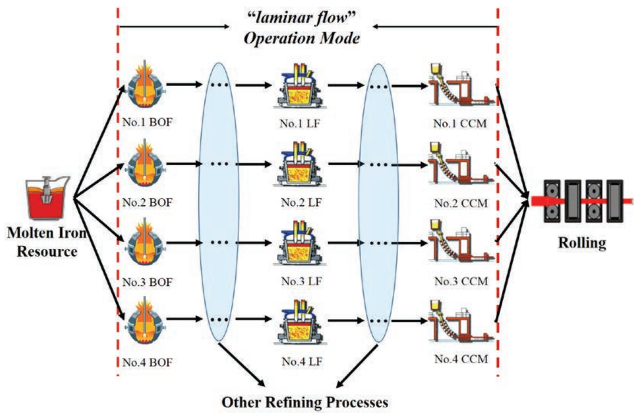

Fig. 2. Schematic diagram of the "laminar flow" operation mode. (Online version in color.)

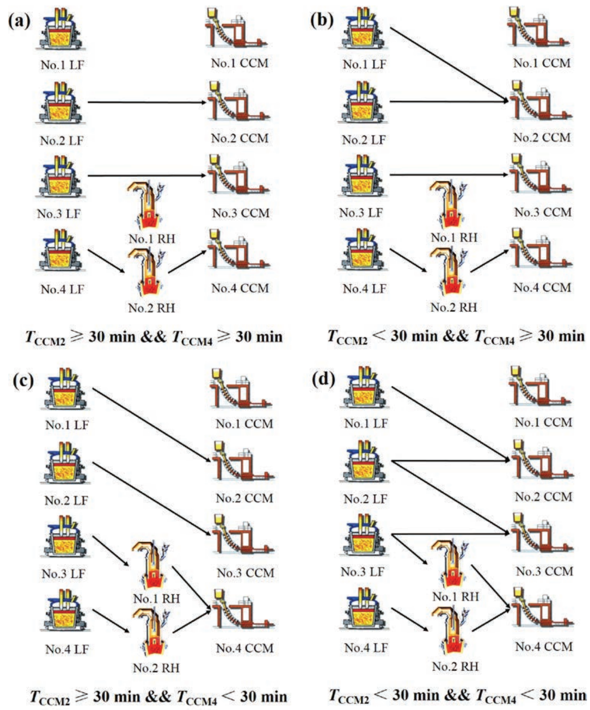

Fig. 3. "LF (RH)–CCM matching" modes when No. 1 CCM is unavailable. (Online version in color.)

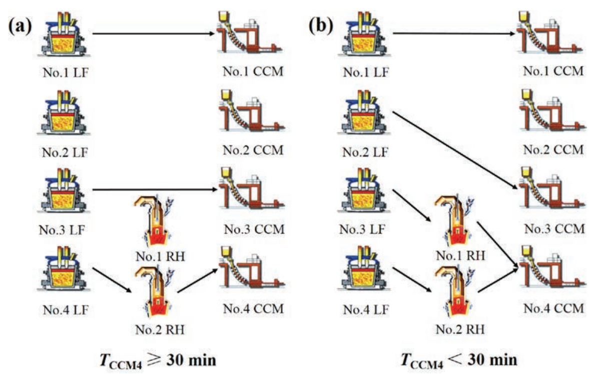

Fig. 4. "LF (RH)–CCM matching" modes when No. 2 CCM is unavailable. (Online version in color.)

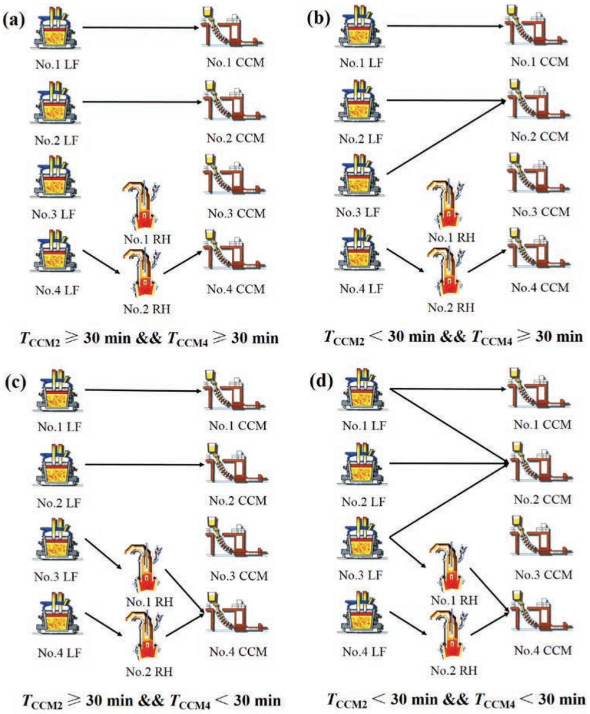

Fig. 5. "LF (RH)–CCM matching" modes when No. 3 CCM is unavailable. (Online version in color.)

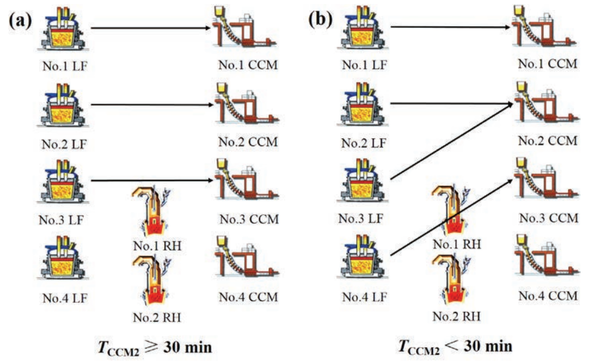

Fig. 6. "LF–CCM matching" modes when No. 4 CCM is unavailable. (Online version in color.)

rent production plans and the operating states of each CCM.

3.1.2. Assignment of Converters Based on Greedy Strategy

Seen from Table 3, it is very difficult to find out the relatively fixed corresponding relations between BOFs and CCMs (LFs) resulted from the larger difference of their processing times. Therefore, the greedy strategy is introduced to solve the assignment problem of BOFs. The mechanism of greedy strategy is to calculate the expected starting times and expected completion times of the unassigned heat in each BOF and choose the one based on the minimization on operation conflictions with the heats that have been arranged to it. In addition, the uncertainty of LF (RH) assignment, such as the case of selecting LF for No. 2 CCM in Fig. 5(d), is also solved by the proposed greedy strategy. The detailed procedures for device assignment in terms of greedy strategy are given as follows.

Firstly, the calculations of expected starting time and completion time are revealed as Eqs. (14)–(18).

(1) No redundant waiting among different processes

$$\begin{aligned} t^*_{i,j+1,k_{i,j+1}} &= c^*_{i,j,k_{ij}} + T^{i,j+1,k_{i,j+1}}_{i,j,k_{ij}} \\ &= t^*_{i,j,k_{ij}} + P_{ij} + T^{i,j+1,k_{i,j+1}}_{i,j,k_{ij}}, \forall i \in I, j \in J_i^* \end{aligned} \quad \text{.... (14)}$$

(2) Casting as planned

$$t^*_{FH(n),|J_{FH(n)}|} = T_n, n \in N \quad \text{..................... (15)}$$

Then the expected starting cast times of other heats in cast n are calculated by Eq. (16).

$$t^*_{i+1,|J_{i+1}|} = t^*_{i,|J_i|} + P_{i,|J_i|}, \forall i, i+1 \in I_n, n \in N \quad \text{.......... (16)}$$

Further, the expected starting times and completion times of each heat in other processes are calculated as Eqs. (17)–(18).

$$t^*_{ijk} = \begin{cases} t^*_{i,|J_i|} - P_{ij} - T^{i,j+1,k_{i,j+1}}_{i,j,k} & , j = |J_i^*| \\ t^*_{i,|J_i|} - \sum\limits_{j'=j+1}^{|J_i^*|} (P_{ij'} + T^{i,j'+1,k_{i,j'+1}}_{i,j',k_{ij'}}) - P_{ij} - T^{i,j+1,k_{i,j+1}}_{i,j,k}, & j = 1,2,...,|J_i^*| - 1 \end{cases}, \forall i \in I, k \in M_j \quad \text{.. (17)}$$

$$c^*_{ijk} = t^*_{ijk} + P_{ij}, \forall i \in I, j \in J_i^*, k \in M_j \quad \text{............ (18)}$$

If assigning device for heat q in process j, the first step is to calculate the expected starting times and completion times of heat q in each device of process j. The next step is to choose device from process j for heat q in sequence based on device index from 1 to $|M_j|$, and then respectively identify the positional relations between heat q and its adjacent heats in each device of process j. The predictable positional relations between heat q and its adjacent heat i in device k of process j are depicted in **Fig. 7**, where Figs. 7(c)–7(f) display the possible conflict cases, and the green region presents the conflict range.

For minimizing operation conflictions, define the conflict functions of Eqs. (19)–(20) used to calculate the total conflict values of heat q with its adjacent heats in each optional device.

$$F_j(q,E,k) = \sum_{i \in I} f_i(q,i,k) \text{ and } F_j(q,\varnothing,k) = 0, j \in J_q^*, k \in M_j \quad \text{.. (19)}$$

$$f_i(q,i,k) = \begin{cases} \min(c^*_{qjk}, c^*_{ijk}) - \max(t^*_{qjk}, t^*_{ijk}), [t^*_{qjk}, c^*_{qjk}] \cap [t^*_{ijk}, c^*_{ijk}] \neq \varnothing, i \in E_{jk} \\ 0 \quad , \quad \text{otherwise} \end{cases} \quad \text{.. (20)}$$

If more than one device meet the minimum on operation confliction for heat q, three following sorts of strategies are used to further identify the suitable one. Three strategies are developed on account of the minimum on transportation time, the minimum on workload and the earliest available device. The detailed expressions of three strategies are formulized as follows.

(1) Strategy of the minimum on transportation time, named as $\boldsymbol{S_1}$

$$T_{tran}(q,j,k) = \min_{k \in M_j} T^{q,j+1,k_{q,j+1}}_{q,j,k}, j \in J_q^* \quad \text{............ (21)}$$

(2) Strategy of the minimum on workload, named as $\boldsymbol{S_2}$

$$L_{load}(q,j,k) = \min_{k \in M_j} L_{load}(j,k) = \min_{k \in M_j} \sum_{i \in E_{jk}} P_{ij}, j \in J_q^* \quad \text{....... (22)}$$

(3) Strategy of the earliest available device, named as $\boldsymbol{S_3}$

$$T_{earl}(q,j,k) = \min_{k \in M_j} T_{earl}(j,k) = \min_{k \in M_j} \max_{i \in E_{jk}} (t^*_{ijk} + P_{ij}), j \in J_q^* \quad \text{.. (23)}$$

Even though the greedy strategy may cause the cross-supply of molten steel from BOF to LF, it could not obviously enhance the scheduling difficulty for cranes owing to four sets of BOFs close to each other in the same span. So the greedy strategy is the appropriate candidate for BOF assignment.

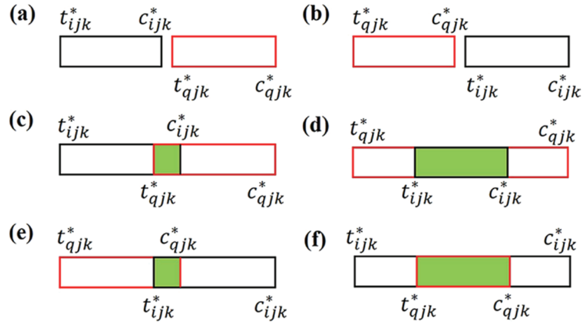

Fig. 7. Predictable positional relations between heat q and heat i. (Online version in color.)

3.2. Conflict Elimination Strategy

After completing device assignments for all heats, a rough scheduling solution is obtained with some unavoidable operation conflictions, and the next step is to eliminate these conflictions. Here, the prior heat adjacent heat i in the same device of process j is defined as $NH(i, j)$. Owing to the devices of each heat in their process routes having been determined by the strategy of device assignment, solving continuous variables, the starting times and completion times of each heat, becomes the unique work in this section. The specific model used to eliminate conflictions is established based on the linear programming method, just as follows:

$$\min\ (f_1 + f_2 + f_3)$$

s.t.

$$t_{NH(i,j),j,k_{NH(i,j),j}} \geq c_{i,j,k_{ij}}, \forall i \in I, j \in J_i \quad \text{............ (24)}$$

(7), (13).

Where f_1, f_2, and f_3 respectively indicate the objective functions corresponding to Eqs. (1)–(3), in which the details of device assignments for each heat are known.

The conflict elimination is carried out through three procedures below.

Step 1: Fix the expected starting time and completion time of the last heat in each LF (RH) and then forwardly update starting times and completion times of other heats in the same refining device just as Eq. (24). If the conflicting time between two adjacent heats is equal to t min, both starting time and completion time of the previous heat shift forward t min.

Step 2: Update the starting times and completion times of heats in each BOF (LF) as the constraint (7) on the basis of the results in Step 1, and eliminate operation conflictions in each BOF (LF) using the same method in Step 1.

Step 3: If the starting time of the first heat in each BOF is larger than the earliest available time of the corresponding BOF, the conflict elimination is completed, otherwise, eliminate the remaining conflictions by delaying the starting time in CCM.

3.3. Solution Procedure of Heuristic Algorithm

According to above descriptions, the solving procedure of the proposed heuristic algorithm based on the optimization of "furnace-caster matching" mode is displayed as **Fig. 8**. In Fig. 8, the strategy of the earliest available device is used to assign BOF (LF) when there are more than one BOFs (LFs) meeting the minimization on conflictions. In particular, the process numbers of heats in the process routes of BOF→LF→CCM and BOF→LF→RH→CCM are respectively 4 and 5 due to LF with double-station divided two single stages of heating refining and soft blowing. While the process number of heats in the process route of BOF→RH→CCM is 3 since RH is generally used as single-station.

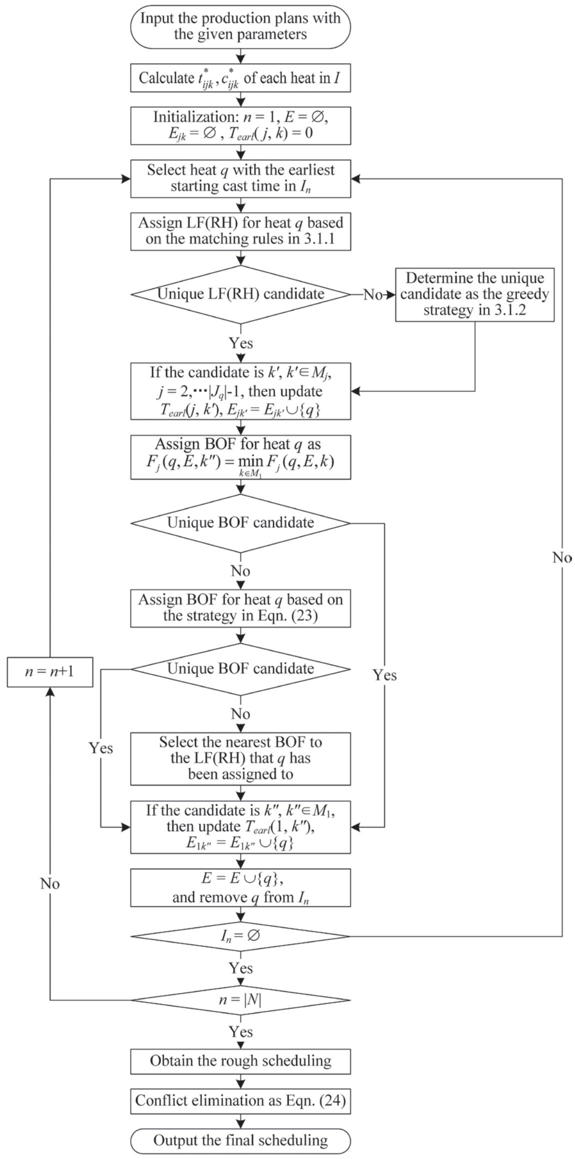

Fig. 8. Flow chart of the proposed heuristic algorithm.

4. Experiment and Discussion

4.1. Experiment Instances

Instead of being generated randomly by computer, the experiment instances in this paper are chosen from actual production plans, and the representative instances are singled out as shown in **Tables 4** and **5**, where the production plan in Table 4 is named as Instance 1 and the one in Table 5 is named as Instance 2.

4.2. Experiment Parameter Set

According to the analysis of actual production data, there isn't an obvious relation between the processing times of heats in BOF (LF/RH) and their steel grades. Thus, the processing times of BOF, LF and RH are respectively set as 40 min, 42 min (30 min for heating and 12 min for soft blowing) and 30 min based on the statistical results in Table 3. With respect to the continuous casting stage, the casting times of each CCM just depend on the section sizes of molds since the weight of molten steel for casting is relatively stable in the studied plant. The casting times of heats in two instances are displayed in **Table 6**.

In addition, the penalty coefficients of optimal objectives

Table 4. Instance 1 for simulation experiment.

Caster	Casting Sequence	Heats in Cast	Starting Time	Completion Time
No. 1 CCM	1	22	16:00 28.10.2018[a)]	09:30 29.10.2018
No. 2 CCM	3	30	20:00 28.10.2018	11:30 29.10.2018
No. 3 CCM	4	5	07:30 29.10.2018	12:30 29.10.2018
No. 4 CCM	2	26	19:30 28.10.2018	07:30 29.10.2018

[a)]: hour: minute day. month. year.

Table 5. Instance 2 for simulation experiment.

Caster	Casting Sequence	Heats in Cast	Starting Time	Completion Time
No. 1 CCM	–	–	–	–
No. 2 CCM	1	31	18:30 02.11.2018[a)]	13:00 03.11.2018
No. 3 CCM	2	21	01:00 03.11.2018	21:30 03.11.2018
No. 4 CCM	3	24	04:30 03.11.2018	18:30 03.11.2018

[a)]: hour: minute day. month. year.

Table 6. Casting times of heats in Instance 1 and Instance 2.

Caster	No. 1 CCM		No. 2 CCM		No. 3 CCM		No. 4 CCM	
	Ins. 1	Ins. 2	Ins. 1	Ins. 2	Ins. 1	Ins. 2	Ins. 1	Ins. 2
Casting Time/min	47	–	31	35	56	56	27	34

Table 7. Penalty coefficients of the optimal objectives.

Penalty Coefficient	$C1_n$/min^{-1}	$C2_n$/min^{-1}	$C3_i$/min^{-1}	$C4_k$/min^{-1}
Values	0.8	1.0	1.2	0.5

are identified based on the relative importance of each objective in actual production. Their values are shown in **Table 7**.

4.3. Experiment Design and Result Analysis

Aiming at the requirements of high efficiency and low cost to solve practical scheduling problems, two sorts of popular algorithms, heuristic algorithms and genetic algorithms, are applied to solve instances and determine the suitable candidate. In addition, above two sorts of algorithms are also improved based on the characteristics of scheduling problem in the studied plant. The detailed illustrations for them are given below.

Besides the proposed heuristic algorithm ($\boldsymbol{A_1}$) in this paper, two sorts of other heuristic algorithms are also utilized to make the comparisons, and the features of them are listed below.

(1) Heuristic Algorithm-I ($\boldsymbol{A_2}$): Both the "furnace-caster matching" modes and the configuration characteristics of LF are not considered in this algorithm, and its solutions for scheduling problems are just based on the proposed greedy strategy.

(2) Heuristic Algorithm-II ($\boldsymbol{A_3}$): The configuration characteristics of LF is concerned in this algorithm, and the device assignment is also carried out by the proposed greedy strategy.

Since there are multiple device assignment strategies for algorithms of $\boldsymbol{A_1}$–$\boldsymbol{A_3}$, heuristic algorithms with different assigning strategies are marked as the following rule:

$$\boldsymbol{A_1}+\boldsymbol{S_1}(\text{Eq. 21}):\ \boldsymbol{M_{11}},\ \boldsymbol{A_1}+\boldsymbol{S_2}(\text{Eq. 22}):\ \boldsymbol{M_{12}},$$
$$\ldots\ldots,\ \boldsymbol{A_3}+\boldsymbol{S_3}(\text{Eq. 23}):\ \boldsymbol{M_{33}}.$$

With respect to the improved genetic algorithms (IGA), their parameter settings are illustrated as follows.

(1) IGA-I ($\boldsymbol{A_4}$): The detailed genetic operations, such as coding, crossover, mutation, refer to Ref. [23]. The evolution generation, population size, crossover probability and mutation probability are respectively set as 200/100 and 0.8/0.01 by multiple sets of tests. In particular, the fluctuation coefficient of starting cast time (T_n) is defined as 0 min, which means T_n would not change during iterations.

(2) IGA-II ($\boldsymbol{A_5}$): The fluctuation coefficient of T_n is set as 15 min, which means T_n can change in rang of (T_n-15, T_n+15) min through mutation operation, and other genetic operations are the same as $\boldsymbol{A_4}$.

(3) IGA-III ($\boldsymbol{A_6}$): The fluctuation coefficient of T_n is set as 25 min, which means T_n can change in rang of (T_n-25, T_n+25) min through mutation operation, and other genetic operations are the same as $\boldsymbol{A_4}$.

In addition, the manual scheduling schemes are also given to make comparisons with above algorithms. The algorithms are coded by Microsoft Visual C#, and each algorithm runs 20 times for instances on a PC with Intel(R) i7-3770U CPU/8.0 GB RAM/Window 7. The best solutions of each IGA with the minimum penalty values are reserved to make comparisons with those of the proposed heuristic algorithm.

Not just limited to penalty values, some important indicators that can evaluate the scheduling of individual heat are also made in statistics to further compare the scheduling solutions obtained by different algorithms. These indicators are listed as follows.

(1) The longest transferring time between refining device and caster, which is named as $\boldsymbol{I_1}$ that contains the transportation time from refining device to caster and the waiting time between them.

(2) The ratio of heats whose transferring times between refining device and caster are more than 25 min, which is named as $\boldsymbol{I_2}$.

(3) The largest deviation on T_n, which is named as $\boldsymbol{I_3}$, and the tolerance interval in the studied plant is set as (T_n-30, T_n+30) min.

(4) The longest transferring time between any two adjacent processes, which is named as $\boldsymbol{I_4}$, and its upper limit in the studied plant reaches to 25 min at present owing to the use of ladles with lids.

Through a series of simulation experiments, it is found that each heuristic algorithm just gets the unique solution by testing 20 times, and it is due to the introduction of various assigning rules limiting the randomness of device assignment. The detailed experimental results are exhibited in **Table 8**.

Comprehensively comparing the results of different heuristic algorithms in Table 8, it is found that the failures of the algorithms of $\boldsymbol{A_2}$ and $\boldsymbol{A_3}$ are mainly resulted from $\boldsymbol{I_2}$($\boldsymbol{I_4}$) and $\boldsymbol{I_3}$ seriously exceeding the tolerance values of 25 min and 30 min. But for $\boldsymbol{A_3}$, the more remarkable improvements of $\boldsymbol{I_1}$ and $\boldsymbol{I_2}$ reveal the necessity to consider the characteristics of device configuration in solving scheduling problems. Besides refining devices discussed in this paper, the study on characteristics of converters and casters also should be paid more attention according to the specific scheduling problems. For the scheduling problems referring to duplex process, it is meaningful to study the device characteristics and operation rules of duplex converters since it has become a common technology in Asian region.[1,24)] With regard to the algorithms derived from $\boldsymbol{A_1}$, the introduction of "furnace-caster matching" modes significantly improves their availability with the better indicators. Seen from the solutions obtained by the algorithms derived from $\boldsymbol{A_1}$, the transferring times of heats between refining device and caster are all controlled within 25 min in two instances. Indeed, $\boldsymbol{M_{13}}$ can be regarded as the correct candidate owing to all values of $\boldsymbol{I_1}$–$\boldsymbol{I_4}$ in two instances within the limited range. Of course, the strategy based on the earliest available device is proved as the more effective method for device assignment in this paper. For $\boldsymbol{M_{13}}$, the larger penalty value for Instance 1 against the one of $\boldsymbol{M_{12}}$ is resulted from the longer idle times of BOFs as shown

Table 8. Experimental results obtained by different algorithms.

Solution Algorithm	Penalty Value		I_1/min		I_2/%		I_3/min		I_4/min		Time-Consuming/s
	Ins. 1	Ins. 2	Ins. 1	Ins. 2	Ins. 1	Ins. 2	Ins. 1	Ins. 2	Ins. 1	Ins. 2	
M_{11}	2 305.5	1 465.2	16	17	**0**	**0**	171	84	150	41	3.5
M_{12}	**390.8**	2 042.2	16	18	**0**	**0**	18	58	20	28	3.1
M_{13}	407.3	1 438.6	16	18	**0**	**0**	18	20	20	19	3.3
M_{21}	3 575.5	1 584.5	210	17	20.5	**0**	209	112	210	17	3.8
M_{22}	2 853	1 857.1	67	40	36.1	5.3	65	37	67	40	3.5
M_{23}	5 349	1 849.9	97	40	39.8	3.9	95	37	97	40	3.6
M_{31}	2 166.4	1 533.2	16	17	**0**	**0**	171	84	143	42	**2.9**
M_{32}	2 091	1 595.1	50	25	2.4	2.6	57	26	50	25	3.0
M_{33}	1 798.8	1 537.5	51	21	6.0	**0**	61	20	51	21	**2.9**
A_4	5 257.1	2 673.8	70	47	42.2	18.4	**0**	**0**	82	47	88.6
A_5	934.3	1 737.6	27	25	4.8	5.3	15	15	27	25	90.7
A_6	395	**1 387.7**	**14**	18	**0**	**0**	24	21	**17**	**18**	92.3
Manual	–	–	22	**16**	1.2	**0**	26	21	22	35	≥3 600

Note: The best results for each indicator are shown as bold pattern.

Table 9. Detailed time results of each objective based on A_1.

Solution Algorithm	Total deviation of starting time for casting/min		Total waiting time among different processes/min		Total idle time of BOFs/min	
	Ins. 1	Ins. 2	Ins. 1	Ins. 2	Ins. 1	Ins. 2
M_{11}	171	84	1 405	141	897	2 424
M_{12}	37	153	29	441	638	2 720
M_{13}	38	44	29	73	669	2 614

in **Table 9**. Nevertheless, the high charging temperature of molten iron in the studied steel plant can compensate the temperature drop caused by the longer idle times of BOFs. In addition, it is also observed in Table 9 that the total idle times of BOFs in Instance 1 are obviously shorter than those in Instance 2. That is derived from all BOFs in Instance 2 still in the state of working when No. 1 CCM out of operation, which leads to the low productivity of BOFs along with long idle time. Even though the solutions generated by the manual also can keep the regular production, it usually has to spend more than 1 hour to prepare the scheduling schemes, and the calculation time of M_{13} is just a few seconds. In conclusion, the algorithm of M_{13} is the right candidate to solve the practical scheduling problems in comparison to other heuristic algorithms as well as the manual.

With respect to the results of the improved genetic algorithms, their calculation times are approximately one and a half minutes, whose efficiencies are slightly lower than those of heuristic algorithms. Compared with A_4 and A_5, A_6 is the better solving algorithm as a result of its acceptable results on all indicators. The setting of fluctuation coefficient for T_n is a necessary work to keep the availability of the whole scheduling solution even though it is inevitable to generate some deviations on T_n. In particular, I_4 for two instances obtained by A_6 are shorter than those obtained by M_{13}.

To further evaluate the performances of M_{13} and A_6 under the requirement of "laminar flow" operation, the index of process matching degree is proposed based on the idea of the furnace-caster (device) matching degree[25] to evaluate the matching relations between adjacent processes in scheduling solutions. For the furnace-caster matching degree, it is used to quantify the matching relations of a certain device with the devices in next process. If a certain BOF (LF) supplies molten steel for multiple LFs (CCMs) at the same time, the furnace-caster matching degree will be smallest when each LF (CCM) receives the equal amount of molten steel from this BOF (LF). Oppositely, the furnace-caster matching degree will be largest if a certain BOF (LF) supplies molten steel just for one LF (CCM). The detailed computational formula of the process matching degree is shown as Eq. (25) below. If each BOF (LF) supplies molten steel just for one LF (CCM), as the "laminar flow" operation mode shown in Fig. 2, the process matching degree between BOF (LF) and LF (CCM) is the maximum, namely 100. With more frequent cross-supply of molten steel among processes, the process matching degree will be smaller. Since the achievement of "laminar flow" operation mode is beneficial for production origination, crane scheduling and ladle cycling,[1,22] the larger process matching degree is welcome and indicates the more stable, orderly production in SMCC.

$$R^{P\to N} = \frac{\sum_{i=1}^{m} R_i^{P\to N}}{m} = \frac{\sum_{i=1}^{m} \dfrac{\sum_{j=1}^{n}\left(f_{ij}-\dfrac{1}{n}\right)^2}{1-\dfrac{1}{n}} \times 100}{m} \quad \text{...... (25)}$$

Where $R^{P\to N}$ and $R_i^{P\to N}$ respectively indicate the process matching degree and the furnace-caster matching degree, the value ranges of which are all from 1 to 100; m and n represent the total number of devices used for release and reception of molten steel; i and j present the serial numbers of BOF (LF/RH) and LF/RH (CCM); f_{ij} stands for the ratio of molten steel amount from No.i BOF (LF/RH) to No.j LF/RH (CCM) accounting for the total amount processed by No.i BOF (LF/RH), which is calculated by Eq. (26).

$$f_{ij} = \frac{Q_{BOF(LF/RH)_i \to LF/RH(CCM)_j}}{Q_{BOF(LF/RH)_i}} \times 100\% \quad \text{........... (26)}$$

Where $Q_{BOF(LF)_i \to LF(CCM)_j}$ indicates the molten steel amount from No.i BOF (LF/RH) to No.j LF/RH (CCM); $Q_{BOF(LF)_i}$ represents the total amount of molten steel pro-

Table 10. Matching degree of BOF–LF in Instance 1.

Device	The ratio of molten steel from BOF to LF (f_{ij}), %				$R_i^{P\rightarrow N}$	$R^{P\rightarrow N}$
	No. 1 LF	No. 2 LF	No. 3 LF	No. 4 LF		
No. 1 BOF	100.0/12.0	0/32.0	0/32.0	0/24.0	100.0/3.6	38.1/6.3
No. 2 BOF	0/16.7	47.6/33.3	33.3/33.3	19.1/16.7	16.5/4.5	
No. 3 BOF	0/18.8	52.6/18.8	21.1/12.4	26.3/50.0	18.7/11.5	
No. 4 BOF	0/38.9	50.0/27.8	30.0/22.2	20.0/11.1	17.3/5.4	

Note: "a" and "b" in "a/b" respectively stand for the values corresponding to $\boldsymbol{M_{13}}$ and $\boldsymbol{A_6}$.

Table 11. Matching degree of LF–CCM in Instance 1.

Device	The ratio of molten steel from LF to CCM (f_{ij}), %				$R_i^{P\rightarrow N}$	$R^{P\rightarrow N}$
	No. 1 CCM	No. 2 CCM	No. 3 CCM	No. 4 CCM		
No. 1 LF	100.0/41.2	0/35.3	0/5.9	0/17.6	100.0/10.5	86.6/10.7
No. 2 LF	0/12.5	100.0/50.0	0/8.3	0/29.2	100.0/14.4	
No. 3 LF	0/31.8	0/22.7	27.8/4.5	72.2/41.0	46.5/9.7	
No. 4 LF	0/25.0	0/35.0	0/5.0	100.0/35.0	100.0/8.0	

Note: "a" and "b" in "a/b" respectively stand for the values corresponding to $\boldsymbol{M_{13}}$ and $\boldsymbol{A_6}$.

Table 12. Matching degree of BOF–LF in Instance 2.

Device	The ratio of molten steel from BOF to LF (f_{ij}), %				$R_i^{P\rightarrow N}$	$R^{P\rightarrow N}$
	No. 1 LF	No. 2 LF	No. 3 LF	No. 4 LF		
No. 1 BOF	0/17.6	42.1/29.4	26.3/17.6	31.6/35.4	12.8/3.2	13.0/9.1
No. 2 BOF	0/22.2	42.1/33.3	26.3/11.1	31.6/33.3	12.8/4.5	
No. 3 BOF	0/13.0	42.1/8.7	21.1/60.9	36.8/17.4	14.3/23.4	
No. 4 BOF	0/11.1	36.8/38.9	36.8/27.8	26.4/22.2	12.1/5.4	

Note: "a" and "b" in "a/b" respectively stand for the values corresponding to $\boldsymbol{M_{13}}$ and $\boldsymbol{A_6}$.

Table 13. Matching degree of LF–CCM in Instance 2.

Device	The ratio of molten steel from LF to CCM (f_{ij}), %				$R_i^{P\rightarrow N}$	$R^{P\rightarrow N}$
	No. 1 CCM	No. 2 CCM	No. 3 CCM	No. 4 CCM		
No. 1 LF	–/–	–/50.0	–/0	–/50.0	–/24.9	100.0/18.7
No. 2 LF	–/–	100.0/45.0	0/20.0	0/35.0	100.0/4.7	
No. 3 LF	–/–	0/25.0	100.0/66.7	0/8.3	100.0/27.0	
No. 4 LF	–/–	0/50.0	0/5.0	100.0/45.0	100.0/18.2	

Note: "a" and "b" in "a/b" respectively stand for the values corresponding to $\boldsymbol{M_{13}}$ and $\boldsymbol{A_6}$.

cessed by No.i BOF (LF/RH).

For the scheduling solutions solved by $\boldsymbol{M_{13}}$ and $\boldsymbol{A_6}$, their results about the process matching degree as well as furnace-caster matching degree are obtained according to Eqs. (25)–(26) and shown in **Tables 10–13**.

Seen from Tables 10–13, $R^{P\rightarrow N}$ and $R_i^{P\rightarrow N}$ of scheduling solutions solved by $\boldsymbol{M_{13}}$ are significantly larger than those obtained by $\boldsymbol{A_6}$, which is resulted from the introduction of "furnace-caster matching" modes. Compared to the operations of crossover and mutation to assign BOF in $\boldsymbol{A_6}$, the BOF assignment based on greedy strategy could improve the matching relations between BOF and LF. Indeed, the scheduling with larger $R^{P\rightarrow N}$ and $R_i^{P\rightarrow N}$ is closer to the "laminar flow" operation mode, and thus, $\boldsymbol{M_{13}}$ is superior to $\boldsymbol{A_6}$ based on the view of process matching.

In addition, the evaluation on performance of algorithms should pay more attention to some key factors closely related to actual production, such as the consideration on the running of multiple cranes[26] and the cycling (turnover) of ladles online,[27] not just limited to the comparison on penalty values of objective functions. In this paper, the simulation model based on Plant Simulation software is applied to run the scheduling solutions solved by $\boldsymbol{M_{13}}$ and $\boldsymbol{A_6}$ with crane non-collision constraint, and further verify the availability of algorithms in practice. The procedures for simulating are illustrated in details in Ref. [28], and the rules of crane assignments for heats are provided by the studied plant. The indices used to evaluate the simulation results involve the total completed times of each instance, the turnover numbers of ladles for each instance, and the transferring times of heats among different processes. The simulation results are shown in **Table 14** and **Figs. 9**, **10**. In particular, the strategy of ladle exchange,[29] meaning a certain ladle could be used in succession for different production lines, is not applied in the studied plant due to the difference in chemical composition of steel grades produced by different CCMs. Thus, it is reasonable to calculate the turnover number of ladles through counting the number of ladles cycling around each CCM.

For the simulated results of scheduling solutions of each instance solved by $\boldsymbol{M_{13}}$, almost all evaluation indices of them in Table 14 are better than those of $\boldsymbol{A_6}$. The shorter total completed times originated from $\boldsymbol{M_{13}}$ means the higher production efficiency, which is beneficial to raise the output. For Instance 1, the release of one more ladle in the scheduling solution solved by $\boldsymbol{A_6}$ compared with the one of $\boldsymbol{M_{13}}$ would lead to the higher production cost, and the need of more ladles for No. 2 CCM and No. 4 CCM is resulted from their shorter casting cycles. In Figs. 9, 10, the distributions on the transferring

Table 14. Comparisons on simulation results of scheduling solutions solved by M_{13} and A_6.

Ins.	Solution Algorithm	Total Completed Time/min	Turnover Number of Ladles/Sets				Mean Transferring Time/min		
			No. 1 CCM	No. 2 CCM	No. 3 CCM	No. 4 CCM	BOF–LF	LF–CCM	RH–CCM
1	M_{13}	1 307.6	4	5	4	8	10.9	11.6	11.4
	A_6	1 314.5	4	6	4	8	11.7	12.2	11.1
2	M_{13}	1 662.8	–	5	4	7	9.8	11.2	10.7
	A_6	1 667.3	–	5	4	7	10.2	11.9	10.8

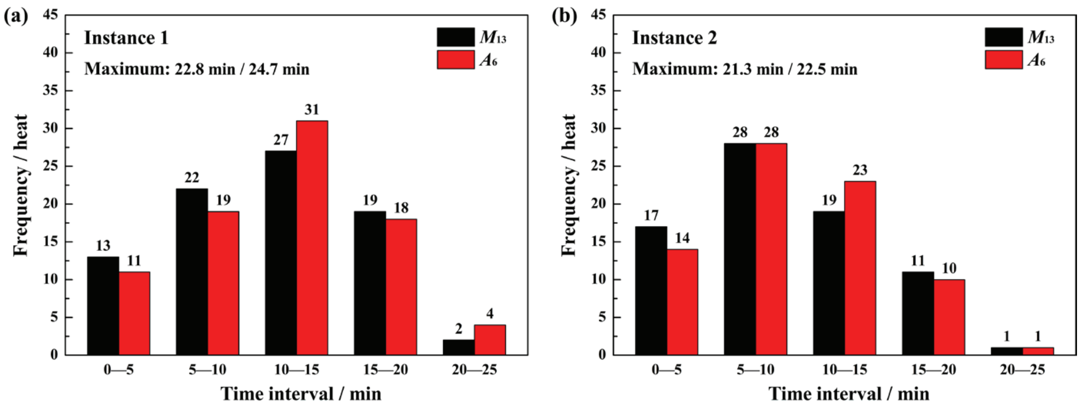

Fig. 9. Distributions on the transferring times of heats from BOF to LF. (Online version in color.)

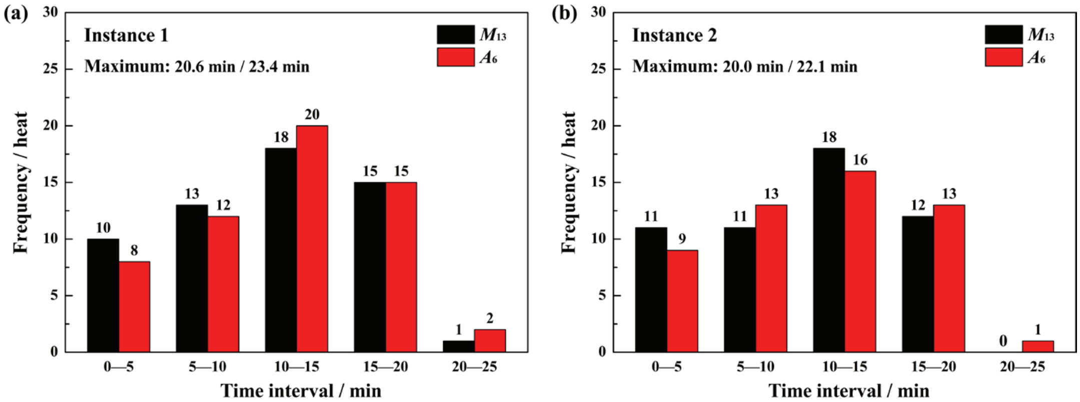

Fig. 10. Distributions on the transferring times of heats from LF to CCM. (Online version in color.)

Fig. 11. Interface presentation of production scheduling. (Online version in color.)

times of heats from BOF (LF) to LF (CCM) in Instance 1–Instance 2 are drawn, and their maximums are revealed as the form of "X/Y", which respectively indicate the longest transferring times in the scheduling solutions of $\boldsymbol{M_{13}}$ and $\boldsymbol{A_6}$. It is not hard to see from Figs. 9, 10 that the transferring times of all heats in two instances are within the upper limit of 25 min, and the heat number in time interval of 5–10 min for $\boldsymbol{M_{13}}$ is slightly more than that for $\boldsymbol{A_6}$. In fact, it is also acceptable that the transferring times of heats among processes are a little longer than 25 min by moderately raising the heating power of LF to compensate excessive heat loss. In addition, the longest transferring times of heats among processes in Figs. 9, 10 are all larger than those in Table 8, which demonstrates the effect of cranes on mass flow operation should be given enough attention. Through the analysis on above simulation results, it could be concluded that algorithm $\boldsymbol{M_{13}}$ is the more correct candidate to solve the complex scheduling problems from the practical steelmaking-continuous casting production.

At present, the scheduling model and heuristic algorithm based on the matching of "furnace to caster" have been utilized to develop a scheduling system that has successfully run in the studied plant. The obtained scheduling solutions can keep the orderliness, stability, high efficiency and continuity of production operation without loss of production capacity. **Figure 11** displays the interface of production scheduling in the form of Gantt chart, and the scheduling information of each heat is shown as the form of text inside rectangular bars. In addition, the planners can adjust scheduling solutions according to real-time production information and keep the stability of mass flow operation.

5. Conclusions

Focused on the practical scheduling problem in steel plants with the complex layout of lacking refining span, a mathematical scheduling model is established aiming at the optimization of the deviation on starting cast times, the waiting times of heats among different processes and the idle times of converters. Based on the purpose for orderly operation of mass flow, a heuristic algorithm based on the optimization of "furnace-caster matching" mode is designed to solve this model. The experimental results on practical instances indicate the availability of the proposed algorithm compared with the improved genetic algorithms and the manual. The computation time of the proposed algorithm is just a few seconds. In particular, the scheduling solutions solved by the proposed algorithm reveal the better matching relations among different processes, and their better performances in simulation with crane constraint imply the proposed algorithm is the right candidate for the practical steelmaking-continuous casting production.

Indeed, the heuristic algorithm has been studied and used for a long time, but its high efficiency should be notable to solve practical scheduling problems, especially for the steel plants with the complex layout and production scenario. In addition, the optimization of actual production modes should be given more concerns owing to its effectiveness to improve the scheduling algorithms. In future work, the scheduling methods combining different algorithms will be developed based on the optimal production modes and used to solve practical scheduling problems.

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REFERENCES

1) R. Y. Yin: Theory and Methods of Metallurgical Process Integration, Metallurgical Industry Press, Academic Press and Cambridge, MA, (2016), 102.
2) R. Zhong, X. Xu, E. Klotz and S. Newman: *Engineering*, **3** (2017), 616.
3) C. H. Lim, M. J. Kim, J. Y. Heo and K. J. Kim: *J. Intell. Manuf.*, **29** (2018), 497.
4) C. Yin, P. C. Deng and X. B. Li: *J. Adv. Manuf. Syst.*, **17** (2018), 533.
5) Q. Liu, B. Wang, Z. Wang, B. Wang, F. M. Xie and J. Chang: *Mater. Today: Proc.*, **2** (2015), S348.
6) T. Emi: *ISIJ Int.*, **55** (2015), 36.
7) J. Birat: *Metall. Res. Technol.*, **113** (2016), 201.
8) D. Liao, S. Sun, S. Waterfall, K. Boylan, N. Pyke and D. Holdridge: Proc. 6th Int. Cong. on the Science and Technology of Steelmaking (ICS 2015), The Chinese Society for Metals, Beijing, (2015), 107.
9) L. Cao, Y. Wang, Q. Liu and X. Feng: *ISIJ Int.*, **58** (2018), 573.
10) Y. Sahai: *Metall. Mater. Trans. B*, **47** (2016), 2095.
11) L. Tang, J. Liu, A. Rong and Z. Yang: *Eur. J. Oper. Res.*, **133** (2001), 1.
12) K. Mao, Q. Pan, X. Pang and T. Chai: *Eur. J. Oper. Res.*, **236** (2014), 51.
13) S. Yu and T. Chai: *Control Theory Appl.*, **33** (2016), 1413 (in Chinese).
14) L. Tang, Y. Zhao and J. Liu: *IEEE Trans. Evol. Comput.*, **18** (2014), 209.
15) R. Y. Yin: *Iron Steel*, **52** (2017), 1 (in Chinese).
16) Q. Liu, N. Tian and R. Yin: *Chin. J. Process Eng.*, **3** (2003), 171 (in Chinese).
17) G. Wang, B. Wang, B. Wang, C. Wang, Y. Mu, B. Wang, Q. Liu, F. Xie, H. Li, X. Nie and X. Lu: *J. Univ. Sci. Technol. Beijing*, **35** (2013), 1080 (in Chinese).
18) Z. Gu, A. Xu, J. Chang, S. Li and Y. Xiang: *J. Iron Steel Res. Int.*, **21** (2014), 17.
19) S. Yuan, T. Li and B. Wang: *Comput. Integr. Manuf. Syst.*, **25** (2019), 115 (in Chinese).
20) R. Ruiz and J. A. Vázquez-Rodríguez: *Eur. J. Oper. Res.*, **205** (2010), 1.
21) Z. Zheng, J. Y. Long, X. Q. Gao, Y. M. Gong and W. Z. Hu: *Comput. Integr. Manuf. Syst.*, **20** (2014), 2660 (in Chinese).
22) R. Y. Yin: *Iron Steel*, **44** (2009), 1 (in Chinese).
23) Z. J. Xu, Z. Zheng and X. Q. Gao: *Control Decis.*, **31** (2016), 1394 (in Chinese).
24) W. Shim, W. Jang and Y. Kim: Proc. Iron and Steel Technology Conf. (AISTech 2016), AIST, Warrendale, PA, (2016), 1067.
25) Y. Q. Mu, J. Yin, F. M. Xie, B. Wang, B. Wang, C. Wang, Q. Liu, X. C. Lu, L. Q. Zhang and S. H. Bai: *J. Univ. Sci. Technol. Beijing*, **35** (2013), 126 (in Chinese).
26) S. Kuyama and S. Tomiyama: *ISIJ Int.*, **56** (2016), 820.
27) Z. Wei, T. Zhu, T. Z. He and S. X. Liu: *ISIJ Int.*, **54** (2014), 2588.
28) J. P. Yang, J. S. Zhang, M. Guan, Y. J. Hong, S. Gao, W. D. Guo and Q. Liu: *Metals*, **9** (2019), 1078.
29) B. F. Huang, N. Y. Tian, Z. Shi and W. Ma: *J. Iron Steel Res. Int.*, **24** (2017), 617.