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Complete Modification Rescheduling Method and Its Application for Steelmaking and Continuous Casting

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Abstract: Delayed processing time and machine failures upset the plan in steelmaking-continuous casting (SCC) production, which make production plan infeasible. The manual repairing cannot satisfy objectives of quick response and optimal scheduling. The practical rescheduling with 1-4 refining stages cannot abstract as three stages hybrid flow shop (HFS). A method is presented for the rescheduling problem, which includes two steps. Firstly, the assigning machine strategy and its computing algorithm are given. Secondly, the mathematical models are developed as multi-objective model based on practical production constraints, so as to solve machine conflicts. The dynamic scheduling system for SCC with the rescheduling method has been successfully applied to Shanghai Baoshan steel plant, and realizes rapidly optimal rescheduling.

1. INTRODUCTION

SCC process is the core stages in modern iron and steel enterprise, which includes three processing stages, namely steel making, refining and continuous casting. There are high expectations for processing and transportation time, temperature and quality ingredients, and the production capabilities are sufficiently exerted on the basis of continuous production. As such SCC schedule problem is considered to be the most challenge one. Rescheduling of SCC process is the process of making new schedule plan ensuring continuous and stability production, when the processing and transportation time, temperature and quality component of molten steel change and unfeasible schedule plan occurs. It is highly significant to solve the SCC rescheduling problem in practice.

The literatures on SCC scheduling method are mostly focused on the static schedule problem. On the basis of JIT method, the nonlinear integral programming model is established for solving machine conflicts after the charge scheduled, and it is then converted into linear programming model which can be solved using standard linear programming (Lixin Tang, 2002). Lixin Tang and Hua Xuan (2002 2007) abstract SCC as 3 stages HFS problem, and establish static schedule model which can be solved using the Lagrangian relaxation method. VIKAS KUMAR (2006) uses the Auction-based method to solve the schedule problem of SCC, and gets the desired results. However, literatures about rescheduling problem of SCC are quite few. Dongfen GUO (2007) transferred SCC as 3 stages HFS problem and solved the problem using the restriction content theory. The utility and stability are presented for measuring rescheduling methods (Peter Cowling, 2002 2003). The development of a knowledge model, which describes the reasoning process in managing schedule disturbance in SCC, is presented (R.ROY and B.A.ADESOLA, 2004). The existing literatures mostly assumed the number of refining stage to be one in SCC process, and SCC schedule problem could be abstracted as 3 stages HFS. However, practically the number of refining stage in a SCC process is from 1 to 4, and SCC schedule problem could not be abstracted as 3 stages HFS problem. Rescheduling problem is highly needed to be solved in the practical production. Since the existing scheduling methods could not be used to the practical production directly, the scheduling (rescheduling) model and method are needed to investigate, considering the practical production constraints.

Rescheduling problem of the practical SCC process is described in this paper. The particular assigning equipment strategy and computing algorithm are given for SCC rescheduling problem with 1-4 refining stage which could not be abstracted as 3 stages HFS. The multi-objective models of starting-stopping machine time are established to solve machine conflicts, which can be solved using standard linear programming. The dynamic scheduling system for SCC with the rescheduling method is successfully applied to Shanghai Baoshan steel plant, and realizes a rapidly optimal rescheduling.

2. COMPLETE MODIFICATION RESCHEDULING ISSUE OF SCC

2.1 Steel making-continuous casting (SCC) process

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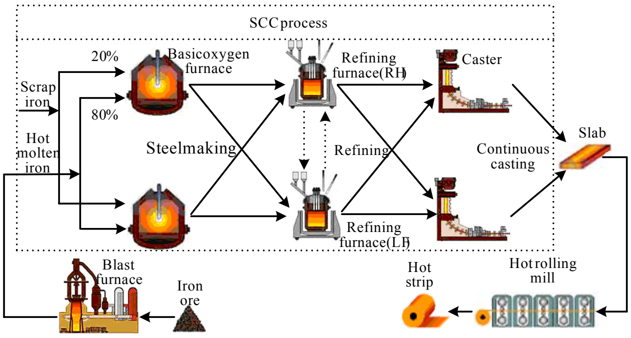

Fig. 1. The SCC production process

SCC production process is composed of three stages namely steel making, refining and continuous casting (Fig.1). (1)Firstly in the process of steel making, molten irons of high temperature are poured into a number of converters (Basic oxygen furnace). Some percent of scrap iron are added to adjust the component. Molten irons are made to molten steel in converters, and controlled the amount of carbon and silicon in techniques need. Molten steel in converters is called a ***Charge***. (2)Secondly in the process of refining, molten steel is transferred via ladles containing one heat of steel, which are transported by a crane to a refining furnace. At refining stage, a charge might undergo 1-4 refining processes, which aim to produce molten steel of the correct grade or chemistry by subjecting the steel to processes that reduce the carbon content, and add alloying additives such as nickel and manganese. A production process on equipment is called ***Unit***. Each charge is made in certain number of refining unit. Each refining unit has the requirement of the refining machine kind. (3)In the last process of continuous casting, molten steel, which matches the need of component and temperature, is drained into a tundish at continuous caster. The molten steel flows into riming machine of continuous caster to cool into the requirement slab. It needs to adjust cost and setup time when continuous caster restarts. To improve the efficiency and reduce the cost, it is needed to make more charges be continuous. That is called one ***Cast***.

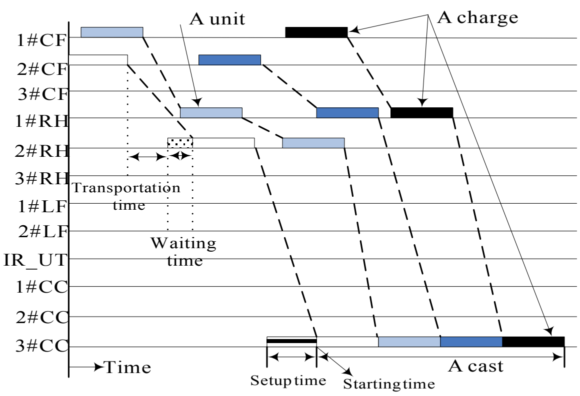

Fig. 2. A processing recipe to complete a case four charges

Taking Baoshan steel plant for example, there are three parallel converters machine of 250t, three kinds of refining machines (including 3 RH machines, 2 LF machines and 1 IR_UT machine) and three parallel continuous casters. In the refining stage, a charge needs 1-4 number of refining process, and a cast includes 4 to 11 charges. Fig.2 shows the schedule of 4 charges, the number of 1 to 4 is the sequence number of these charges. The x-axis is taken to be time, and every line is taken to a machine. Each rectangle is taken to be process time of a unit, and the interval in two immediate units of a charge is the transportation time.

Unlike general production scheduling in machinery industry, SCC production scheduling problems have to meet special requirements of steel production process. (1)In SCC process, the products being processed are handled at high temperature and are converted from liquid (molten steel) into solid (slab). There are extremely strict requirements on material continuity and flow time (including processing time and transportation). (2)Charges are needed to be assembled into cast, and ensuring more charges of a cast to be continuously cast. SCC production scheduling problem is a batch scheduling problem with batch at the least stage (3)The number of refining unit and refining machine kind of a charge are relative with steel grade, therefore the production route of a charge is also related to steel grade.

2.2 Complete Rescheduling Issue of SCC

SCC is a resource schedule problem that highly demands the processing and transportation time, temperature and component with multi-machines, multi-modes, multi-stages and multi-disturbances. SCC production scheduling problems is that: taking the charge as the least element, on the condition of techniques restriction, it is to ensure continuous casting. To obtain optimal estimate function of minimum discontinuity time at continuous casting stage or minimum waiting time at all stages, SCC scheduling problems are determined in what sequence, at what time and on which device molten steel should be arranged at various production stages from steelmaking to continuous casting. The objectives of schedule are that: (1) ensuring more charges of a cast to be continuously cast. (2) there is no waiting or short waiting time for immediate two unit of each charge.

The practical SCC production schedule consists of 3 stages. Firstly, the predictive scheduling is carried out. According to superior plan, scheduler makes scheduling plan, and sends scheduling plan to implement in practice. Secondly, the disturbance events are identified by monitoring starting-stopping time of machine during the running time. Thirdly, when the disturbances occur, perform the adjustments. If part repairing can eliminate the disturbances, the predictive scheduling plan is updated by part repairing. Otherwise, it must carry the complete modification rescheduling. The following discussion emphasizes on the complete modification rescheduling. Typical disturbance events requiring rescheduling in SCC process include the delayed arrival of molten steel and the machine breakdown.

Rescheduling starts when scheduling plan cannot run or need to be improved. At each rescheduling time, the rest unit number of each charge is different. Taking m_i^s ($m_i^s \le m_i$) as the initial unit number of charge i, for example, a charge is smelted or being smelting, then the initial unit number is $m_i^s = 2$, which means that it is rescheduled from the first refining unit.

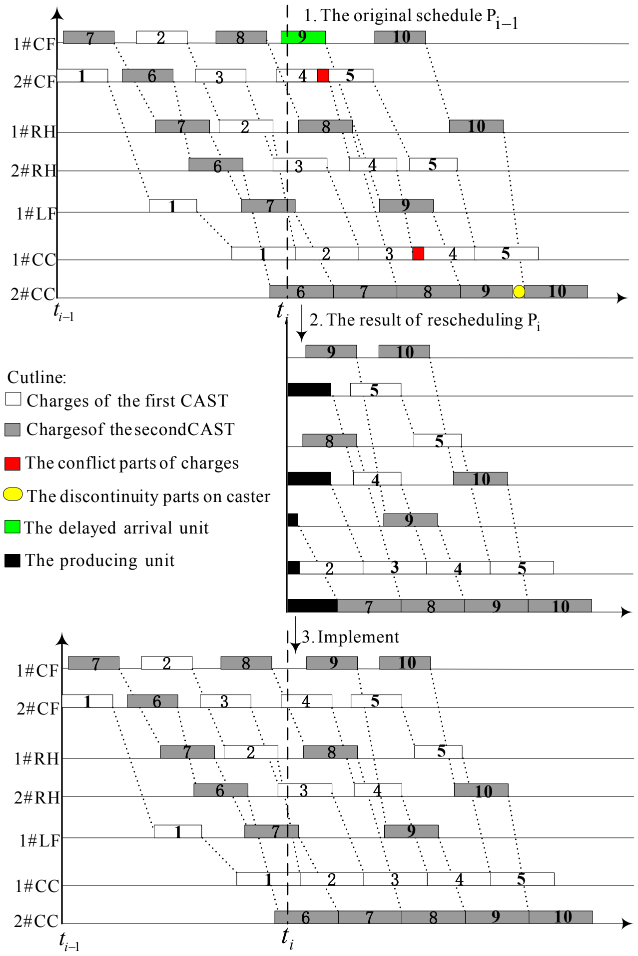

Fig.3.Complete modification rescheduling process

Fig. 3 describes the overall process of complete modification rescheduling, where P_{i-1} is the original schedule plan which operates. The disturbances occur at t_i time, including that the conflict between charge 4 and charge 5 is on 2#CF, the conflict between charge 3 and charge 4 is on 1#CC, discontinuity between charge 9 and charge 10 on 2#CC and the starting time of charge 9 is delayed on 1#CF. P_i is the result of rescheduling at time t_i and the production system starts producing as the arrangement of P_i at time t_i. This is the description of P_{i-1} at time t_i. The units which are producing or finished at time are deleted from the original schedule P_{i-1}. At the same time, the initialization unit number of charge i is modified. If $m_i^s > m_i$, charge i is deleted from the reschedule set totally. Before the rescheduling system is trigged again, the production system is operated as the arrangement of P_i.

3. COMPLETE MODIFICATION RESCHEDULING METHOD OF SCC

The following notations are used for defining rescheduling method parameters and variables in the model.

Parameters

- i — the number of charge, $1 \le i \le n$, where n is the total number of production charges
- m_i — the total unit number of charge i, $3 \le m_i \le 6$, the refining unit is from 1 to 4
- m_i^s — the initialization unit number of charge i, $m_i^s \le m_i$
- j, J — the number of unit, $1 \le j, J \le m_i$, $j' = j+1$
- k — the number of machine, K is the total number of machine
- K_{cc} — the total number of machine on the last stage (continuous casting stage). In figure 2. $1 \le k \le 12$, $K = 12$, $K_{cc} = 3$
- $SI(i,J,k)$ — the immediate foregoing charge of charge i on machine k
- $jc(i)$ — the number of producing unit or fresh produced unit on charge i, $jc(i) < m_i$
- $d(x_{i,j})$ — the processing time of charge i on the machine of unit j
- $t(x_{i,j}, x_{i,j'})$ — the transportation time from the machine of unit j to the machine of unit j'.

Decision variables

- $x_{i,j}$ — the variable of model denotes the starting time of charge i on the j unit, $x_{i,j} = c_{i,j} (j \le jc(i))$
- $k(i,j)$ — the number of processing machine that charge i on unit j

Complete modification rescheduling method does not change processing machine and sequence of every charge on casters. The processing machine are rescheduled on steelmaking and refining stage, and starting-ending time of production machines are also rescheduled on steelmaking, refining and continuous casting stage. The rescheduling method includes two steps: (1) Assigning machine strategy. (2) Elimination of machine conflicts.

3.1 Assigning machine strategy of rescheduling

To describe the assigning machine strategy, we first define the confliction function $f_k(SI(i,J,k), i)$:

$$f_k = \begin{cases} \min(et_{i,j}, et_{SI(i,J,k),J}) - \max(x_{i,j}, x_{SI(i,J,k),J}), \\ \quad [x_{i,j}, et_{i,j}] \cap [x_{SI(i,J,k),J}, et_{SI(i,J,k),J}] \neq \Phi \\ 0, other \end{cases}$$

The sum processing time of conflicts is $\sum f_k(i,k)$ on machine k. The assigning machine strategy is hybrid backward and forward assignment, including the following three steps.

Step1: Sequencing continuous casting unit of charges, and the charges are continuously processed on the same caster, $x_{i,m_i} = x_{SI(i,m_i,M_{cc})} + d(x_{SI(i,m_i,M_{cc})})$.

Step2: Based on the x_{i,m_i} solution of step 1 and $t(x_{i,j}, x_{i,j'})$, $d(x_{i,j})$, according to the shortest route rule, backward ensure processing machine and starting time of each charge on refining stage and steelmaking stage, $x_{i,1}, x_{i,j} (2 \le j \le m_i - 1)$, where conflicts time of machine is not considered.

$x_{i,1}, x_{i,j} (2 \le j \le m_i - 1)$ are computed as follows:

if $(2 \le m_i^s \le m_i - 1)$ and $(m_i^s \le j \le m_i - 1)$ then

{ $x_{i,j} = x_{i,j+1} - t(x_{i,j}, x_{i,j+1})$;

$\Delta t = t(x_{i,m_i^s - 1}, x_{i,m_i^s}) - (x_{i,m_i^s} - x_{i,m_i^s - 1} - d(x_{i,m_i^s - 1}))$

If ($\Delta t > 0$) then

$x_{i,j} = x_{i,j} + \Delta t, x_{i,m_i} = x_{i,m_i} + \Delta t$ }

if $(m_i^s = 1)$ then

{ $x_{i,j} = x_{i,j+1} - t(x_{i,j}, x_{i,j+1})$ }

Step3: Forward ensure processing machines of charge i on all units

Step3.1: Based on the solution of step 2, select a un-assigning and earliest starting time unit (*find* $\min(x_{i,j})$).

Step3.2: Selecting machine $k(i,j)$ that can process $x_{i,j}$ unit and has the smallest sum of conflicts time ($\min \sum f_k(i, k(i,j))$).

Step3.3: If machine $k(i,j)$ is not only, selecting machine $k(i,j)$ to make $t(x_{i,j-1}, x_{i,j})$ smallest by the short route rule ($\min t(x_{i,j-1}, x_{i,j})$).

Step3.4: If un-assigning units of the solution of step 2 still exist, go to step3.1; otherwise, stop.

3.2 Mathematical model of eliminating machine conflicts

After assigning machine, there maybe many conflicts on processing machine and discontinuity on casters. The models are proposed here to eliminate machine conflicts. In section 2.2, the first objective of SCC scheduling is the minimum discontinuity of caster, and the second objective is the minimum waiting time. This problem is multi-constraint and multi-objective, and constraints and objective functions are linear. Lexicographic Order is engaged to deal with precedence of multi-objective linear programming. The variable x ($x > 0$) is the start time of production unit, and current time denotes as zero. The constant c is the start time of producing unit and produced unit, which ensures the correct constraint relation. The variables of continuous casting stage compose of the first stage objective function, and are set as constant to compose of the second stage objective after solving the first stage objective, which ensures that the solution of the first stage objective is not destroyed.

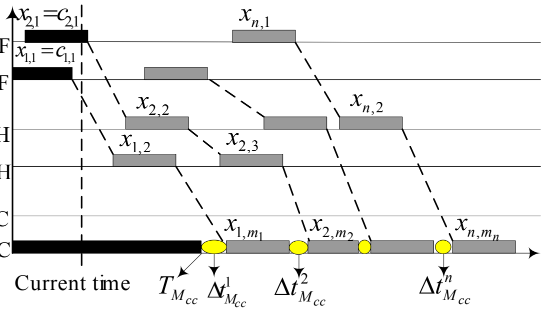

Fig.4 The definition of the first objective variable

The variables and constants are in Fig. 4, where x_{i,m_i} is the starting time of charge i on caster M_{cc} , $\Delta t_{M_{cc}}^i$ is the discontinuity time of charge i on caster M_{cc} , $T_{M_{cc}}$ is the initialization time of caster M_{cc} , $d(x_{i,m_i}) = pt_{M_{cc}}$ is the criterion processing time of charge i on caster M_{cc} .

$x_{1,m_1} = T_{M_{cc}} + \Delta t_{M_{cc}}^1$

$x_{2,m_2} = T_{M_{cc}} + \Delta t_{M_{cc}}^1 + pt_{M_{cc}} + \Delta t_{M_{cc}}^2$

…

$x_{n,m_n} = T_{M_{cc}} + \Delta t_{M_{cc}}^1 + \Delta t_{M_{cc}}^2 + \ldots + \Delta t_{M_{cc}}^n + (n-1) pt_{M_{cc}}$

From these, the following are obtained:

$\sum_{i=1}^{n} x_{i,m_i} = n\Delta t_{M_{cc}}^1 + \ldots + 2\Delta t_{M_{cc}}^{(n-1)} + \Delta t_{M_{cc}}^n + nT_{M_{cc}} + (\sum_{i=1}^{n-1} i) pt_{M_{cc}}$

where $nT_{M_{cc}}$ and $(\sum_{i=1}^{n-1} i) pt_{M_{cc}}$ are constants. Since the foregoing discontinuities severely impact back charges, the penalty weight coefficient of the foregoing discontinuity is great. Hence, $f_1(x) = \sum_{i=1}^{n} x_{i,m_i}$, and $Min(f_1)$ denotes the smallest discontinuity penalty. From the above analysis, it can be seen that the first optimal objective be defined as follows:

$$f_1(x) = \min\left\{\sum_{i=1}^{n} x_{i,m_i}\right\} \tag{1}$$

S.T.

$$x_{i,j'} - x_{i,j} \ge d(x_{i,j}) + t(x_{i,j}, x_{i,j'}), j' = j+1 \tag{2}$$

$$x_{i,j} = c_{i,j}, j \le jc(i) \tag{3}$$

$$x_{i,j,k} - x_{SI(i,J,k),J,k} \ge d(x_{SI(i,J,k),J,k}), k = 1,\ldots,K \tag{4}$$

$$x_{i,j,k} = \begin{cases} c_{i,j}, j \le jc(i) \\ x_{i,j}, j > jc(i) \end{cases} \tag{5}$$

$$x_{i,j} \ge 0, 1 \le i \le n, 1 \le j \le m_i \tag{6}$$

Constraint (2) ensures that for contiguous operation of the same charge, only when the preceding operation is completed and the charge is transported to the next machine, the immediately next operation on the charge can be started. Constraint (3) represents that producing unit and produced unit of the charge i are set as constant. Constraint (4) ensures that for two contiguous charges processed on the same machine, only when the preceding charge is finished, the immediately next one can be started. Constraint (5) represents that the value of the charge i on the machine k relies on unit j, the value of producing unit or produced unit is constant. After the values of producing unit and produced unit are set as constant, each stage objective is a linear programming (LP) model of single objective, and is solved by the standard LP method.

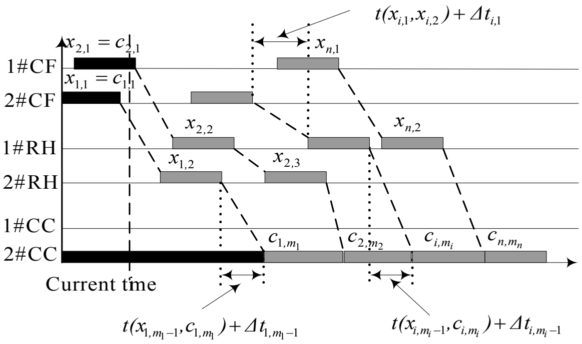

Fig.5 The definition of the second objective variable

After the first stage objective is solved, x_{i,m_i} is set as constant c_{i,m_i} and is saved. In Fig.5, $\Delta t_{i,m_i-1}$ is waiting time of charge i between last refining unit and continuous casting. In Fig.5, the interval time $t(x_{i,m_i-1},c_{i,m_i})+\Delta t_{i,m_i-1}$ of charge i immediate two units is the sum of criterion transportation and waiting time.

$$x_{i,m_i-1}=c_{i,m_i}-\Delta t_{i,m_{i-1}}-t(x_{i,m_i-1},c_{i,m_i})-d(x_{i,m_i-1})$$

$$\dots$$

$$x_{i,1}=c_{i,m_i}-\Delta t_{i,m_{i-1}}-t(x_{i,m_i-1},c_{i,m_i})-d(x_{i,m_i-1})-\Delta t_{i,m_i-2}-t(x_{i,m_i-2},x_{i,m_i-1})-d(x_{i,m_{i-2}})-\dots-\Delta t_{i,1}-t(x_{i,1},x_{i,2})-d(x_{i,1})$$

From these, the following are obtained:

$$\sum_{j=1}^{m_i-1}x_{i,j}=(m_i-1)c_{i,m_i}-[(m_i-1)\Delta t_{i,m_i-1}+(m_i-2)\Delta t_{i,m_i-2}+\dots+\Delta t_{i,1}]-[(m_i-1)t(x_{i,m_i-1},c_{i,m_i})+\dots+t(x_{i,1},x_{i,2})]-[(m_i-1)d(x_{i,m_i-1})+\dots+d(x_{i,1})]$$

where 1,3,4 terms are constant, the second term denotes the sum waiting time of charge i. Continuous casting on caster is strict with steel liquid temperature, and the waiting time can make the steel liquid temperature debasing. Temperature differences are induced due to the waiting time keeping away from continuous casting, which is offset by prolonging processing time of back refining unit. Then the penalty is severe for the waiting time that is close to caster. If $\sum_{j=1}^{m_i-1}x_{i,j}$ is maximized, the sum waiting time of charge i are minimized. From the above analysis, it can be seen that the model of minimum waiting time can be defined as follows:

$$f_2(x)=\max\left\{\sum_{i=1}^{n}\sum_{j=1}^{m_i-1}x_{i,j}\right\}(x_{i,j}\neq c_{i,j}) \qquad (7)$$

$S.T.$

$$x_{i,j'}-x_{i,j}\geq d(x_{i,j})+t(x_{i,j},x_{i,j'}),\ j'=j+1 \qquad (8)$$

$$x_{i,j}=\begin{cases}c_{i,j},\ j\leq jc(i)<m_i\\ c_{i,m_i},\ j=m_i\end{cases} \qquad (9)$$

$$x_{i,j,k}-x_{SI(i,J,k),J,k}\geq d(x_{SI(i,J,k),J,k}),k=1,\dots,(K-K_{cc}) \qquad (10)$$

$$x_{i,j,k}=\begin{cases}c_{i,j},\ j\leq jc(i)\\ x_{i,j},\ j>jc(i)\end{cases},\ k=1,\dots,(K-K_{cc}) \qquad (11)$$

$$x_{i,j}\geq 0, 1\leq i\leq n, 1\leq j\leq m_i-1 \qquad (12)$$

Constraint (8) is the same as constraint (2), which does not include the continuous casting stage. Constraint (9) is the same as constraint (3), and the value of continuous casting stage is set as constant c_{i,m_i}. Constraint (10) is the same as constraint (4), not including casters. Constraint (11) is the same as constraint (5), not including casters.

After solving the model of the second stage, the starting times of production unit on other stages except for continuous casting stage are obtained.

4. APPLICATION

The Shanghai Baosteel steel factory of China produces 1000 kinds steel grade, the number of refining processing ranging from 1 to 4, and refining routes are more than 20 kinds. The computer systems have the level 2 computer system of process control and the level 3 computer system of region management. The practical scheduling system of SCC process only realizes information management, and there are no optimal rescheduling according to disturbance category and degree.

Table 1 original schedule

charge	Steelmaking		refining		casting	
	Starting time	machine	Starting time	machine	Starting time	machine
1	08:49	6#LD	09：32	IR_UT	11:04	4#CC
2	10:04	5#LD	11:00	3#RH	12:10	4#CC
3	10:36	4#LD	11:22	5#RH-1	13:11	4#CC
4	12:24	5#LD	13:10	5#RH-1	14:15	4#CC
5	09:29	4#LD	10:12	IR_UT	11:04	5#CC
6	10:35	6#LD	11:18	IR_UT	12:10	5#CC
7	11:22	4#LD	***12:08***	***5#RH-2***	13:16	5#CC
8	12:42	4#LD	13:25	IR_UT	14:17	5#CC
9	09:01	5#LD	09：57	3#RH	11:04	6#CC
10	09:50	6#LD	***10:36***	***5#RH-2***	12:05	6#CC
11	11:06	5#LD	12:02	3#RH	13:09	6#CC
12	12:23	6#LD	13:06	3#RH	14:13	6#CC

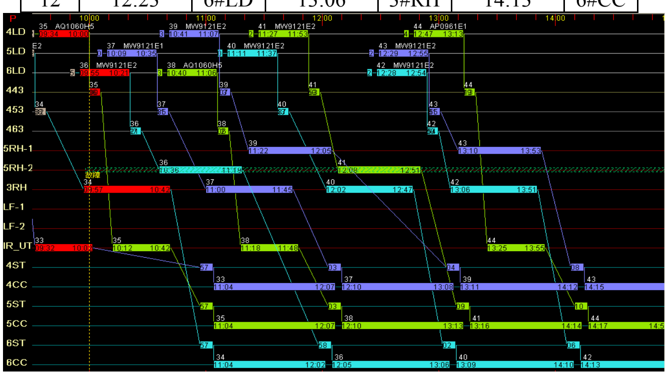

Fig 6 the original schedule Gantt graph

Based on optimal rescheduling methods presented in the paper, the dynamic scheduling subsystem software (Xinfu Pang, 2006) is developed with VC, Delphi, Visual Prolog and database technology, and the complete modification rescheduling is a part of the dynamic scheduling subsystem. The computing time of solving rescheduling is within 25s, scheduling system obtains the optimal result for one day for the largest output 80 stoves within 30 seconds, which may satisfy the real time requirement.

Table 1 is the original schedule that is one group of practical production data, which is generated by the algorithm (Shengping Yu, 2006). There are three casts, 1-12th charges have three units, $m_i = 3$. Cast 1 consists of 1-4th charges that are processed on 4#CC. Cast 2 consists of 5-8th charges that are processed on 5#CC. Cast 3 consists of 9-12th charges that are processed on 6#CC. Fig 6 is the original schedule Gantt graph with failure of 5#RH-2 refining machine.

Table 2 rescheduling results with failure machine

charge	Steelmaking		refining		casting	
	Starting time	machine	Starting time	machine	Starting time	machine
1	08:49	6#LD	09：32	IR_UT	11:04	4#CC
2	10:04	5#LD	11：00	3#RH	12:10	4#CC
3	11:07(*)	5#LD(*)	12:01(*)	3#RH(*)	13:11	4#CC
4	12:24	5#LD	13:10	5#RH-1	14:15	4#CC
5	09:29	4#LD	10:12	IR_UT	11:04	5#CC
6	10:37(*)	4#LD(*)	11:18	IR_UT	12:10	5#CC
7	11:37(*)	4#LD	12:23(*)	5#RH-1(*)	13:16	5#CC
8	12:42	4#LD	13:25	IR_UT	14:17	5#CC
9	09:01	5#LD	09：57	3#RH	11:04	6#CC
10	09:50	6#LD	10:36	5#RH-1(*)	12:05	6#CC
11	10:48(*)	6#LD(*)	11:34(*)	5#RH-1(*)	13:09	6#CC
12	12:23	6#LD	13:06	3#RH	14:13	6#CC

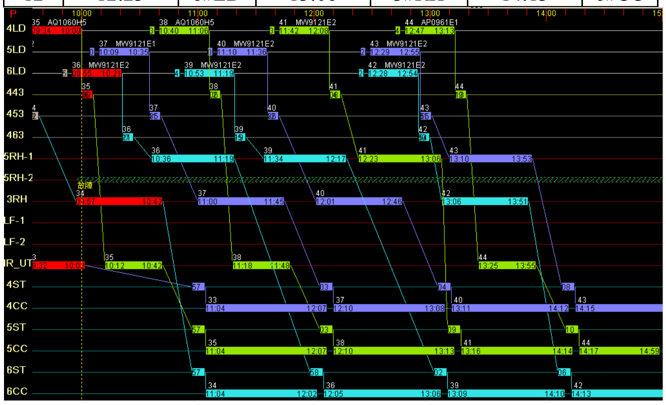

Fig.7 the Gantt graph of rescheduling results

In Table 1, data with underline are produced unit and producing unit, and are set as constants, denoting processing machine and starting-ending time on the machine are immutable. Italic data denote that processing machine and starting-ending time on the 5#RH-2 failure machine. The original schedule cannot be implemented, and the feasible schedule is generated using complete modification rescheduling. The rescheduling result is shown in Table 2, The number or letters with the start symbol on their right express the start times or the processing machines have been changed in the revised schedule. Fig 7 is the rescheduling results in Gantt graph.

5. CONCLUSIONS

Complete modification rescheduling methods for SCC are investigated in this paper. When the original schedule is unfeasible after time delay or machine breakdowns disruption occurring, the new feasible schedule is generated by rescheduling. The rescheduling method includes two steps. Firstly, the charges are assigned to the machines. Secondly, the models are developed as multi-objective programming model, which eliminate machine conflicts. The dynamic scheduling system based rescheduling methods have been applied to a steel factory in Shanghai Baosteel Co. Ltd. The computing time of rescheduling is within 25s, and the rescheduling realization can quickly adjust and largely improve production efficiency. Rescheduling methods of solving problems can be applied to scheduling problems of other steel plants.

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