A Prediction Method for Abnormal Condition of Scheduling Plan with Operation Time Delay in Steelmaking and Continuous Casting Production Process

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In the steelmaking and continuous casting (SMCC) production process, the operation time delay often occurs which may lead to planned casting break or processing conflict so that the initial scheduling plan becomes unrealizable. Existing rescheduling methods with disturbances firstly classify the disturbances according to the disturbance type and disturbance quantity only by artificial experience or rules, and then directly adjust initial scheduling plan with corresponding rescheduling method. Those methods don't analyze the influence degree of disturbances to the initial scheduling plan in detail, so the adjustment degree of initial scheduling plan is always too greater, which leads to the poor continuity and stability of initial scheduling plan. In this paper, the relation among operation time delay, planned casting break and processing conflict is deeply analyzed. Then a novel prediction method for abnormal condition of scheduling plan with operation time delay disturbance in SMCC production process is proposed including disturbance identification of operating time delay based on event-driven mechanism, analysis on charges based on reachability matrix, analysis on influence degree of disturbance and abnormal condition decision of initial scheduling plan. As a result, the real-time application shows that the proposed prediction method can timely and accurately predict the abnormal condition of the scheduling plan with operation time delay disturbance in SMCC production process, which can only adjust the affected charges that must to be rescheduled in the initial scheduling plan and reduce the frequency of complete rescheduling. The initial scheduling plan can also maintain the good continuity and stability.

KEY WORDS: steelmaking and continuous casting; scheduling plan; abnormal condition; planned casting break; processing conflict; prediction.

1. Introduction

The SMCC production process is the core working procedure in modern large steel plant. Due to the process complexity, a large number of machines and frequent changes of the production environment, operation time delay often occurs which may lead to planned casting break or processing conflict so that the initial scheduling plan becomes unrealizable. It is of great significance to quickly and effectively adjust scheduling plan to ensure steel quality and production stability.

Nowadays the studies of rescheduling method for abnormal condition of scheduling plan with disturbances mainly focus on schedule repair and complete rescheduling according to the disturbance type and disturbance quantity. Right-shift rescheduling is adopted for smaller time delay disturbance, which means to reschedule by globally shifting the remaining operations schedule forwards in time. For the quality disturbance, equipment failure or excessive time delay, total rescheduling is used to adjust scheduling plan without consideration of the initial schedule.¹⁾ If disturbance event is very large impact on

production, complete rescheduling is needed which includes production path planning and production time scheduling.²⁾ An algorithm for rescheduling the affected operations in a job shop is presented in order to preserve as much as possible the robustness of the initial schedule, which is different from the right-shift rescheduling and complete rescheduling.³⁾ However, the research on scheduling method for SMCC production process focuses on static scheduling problem,⁴⁻⁶⁾ and rescheduling methods are rarely addressed. The development of a knowledge model including task, inference and domain, which describes the reasoning process in managing schedule disturbance in steel-making, is presented.⁷⁾ A constraint-based approach for steelmaking-continuous casting rescheduling problem is presented for machine failure.⁸⁻¹⁰⁾ A real-time scheduling method is advanced with disturbances event considering four major categories, and a rescheduling algorithm of backward method and hybrid intelligent method is proposed.¹¹⁾ A general framework for using real time information to improve scheduling decisions is developed, and general measures of utility and stability are defined to evaluate strategies for deal with the deal time information.¹²⁾

Existing rescheduling methods with disturbances firstly classify the disturbances according to the disturbance type and disturbance quantity only by artificial experience or rules, and

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then directly adjust initial scheduling plan with corresponding rescheduling method. Those methods include schedule repair for part of charges, complete time rescheduling only adjusting operation time and complete rescheduling including production path planning and production time scheduling. Above methods don't analyze the influence degree of disturbances to the initial scheduling plan in detail, so the adjustment degree of initial scheduling plan is always too greater, which leads to the poor continuity and stability of initial scheduling plan.

In this paper, the disturbance type, disturbance point and disturbance value are firstly determined according to the disturbance event information. Secondly, affected charges are analyzed based on reachability matrix. Then the prediction models of abnormal condition decision of initial scheduling plan without considering buffers and with considering buffers are established to analyze influence degree of operation time delay disturbance to planned casting break and processing conflict, respectively. Finally, abnormal condition of initial scheduling plan is predicted. As a result, the real-time application shows that the proposed prediction method can timely and accurately predict the abnormal condition of the scheduling plan with operation time delay disturbance in SMCC production process, which can only adjust the affected charges in the initial scheduling plan and reduce the frequency of complete rescheduling. The initial scheduling plan can also maintain the good continuity and stability.

The paper is organized as follows. In Section 2, we describe the SMCC production process and the scheduling plan of SMCC production process. The abnormal condition of planned casting break and processing conflict is defined. Section 3 presents a novel prediction strategy for abnormal condition of scheduling plan with operation time delay disturbance in SMCC production process. In Section 4, a novel prediction method for abnormal condition of scheduling plan with operation time delay disturbance in SMCC production process is proposed, which includes disturbance identification of operating time delay based on event-driven mechanism, analysis on charges based on reachability matrix, analysis on influence degree of disturbance and abnormal condition decision of initial scheduling plan. Section 5 presents industrial application in Baosteel factory of China. Finally, conclusions are outlined in Section 6.

2. Prediction Problem Description for Abnormal Condition of Scheduling Plan with Operation Time Delay Disturbance in SMCC Production Process

2.1. Scheduling Plan for SMCC Production Process

Molten steel is firstly smelt in the converter. Then one ladle carries molten steel from one converter to the refining process. Molten steel in the ladle is transported to the continuous caster after refined. One ladle carrying molten steel on the processing of all processes, and the transportation of the ladle among the processes are called a **Charge**. Molten steel in one charge is exactly from one converter and is exactly carried by one ladle. Each charge processed on each machine is regarded as an **Operation** at the processing stage. The operation type and operation number of charge must meet the process requirement. All charges which are continuously drained into the same tundish in a continuous caster are called a **Cast**.

We denote L_{ij} for the j th charge of the i th cast, and $i = 1, \dots, N$, $j = 1, \dots, n_i$, where N indicates the total cast number and n_i represents the total charge number of the i th cast. Each charge L_{ij} consists of θ_{ij} operations ($o_{ij1}, \dots, o_{ij\theta_{ij}}$). Initial SMCC scheduling plan solution S^0 includes the initial processing machine z_{ijk}^0 , the initial starting time s_{ijk}^0 , the initial processing time p_{ijk}^0 , the initial completion time e_{ijk}^0

of operation o_{ijk} ($k = 1, \dots, \theta_{ij}$). In this paper, we denote m_{gb} as the b th machine in the g th machine group. The h_g represents the total number of the g th machine group.

When operation time delay at time t leads to casting break or operation time conflict, the original scheduling plan S^0 becomes unrealizable. It is important to analyze the influence degree of disturbances to the initial scheduling plan in detail in order to maintain the good continuity and stability.

2.2. Operation Time Delay

The actual operation time of charges will often deviate from the initial operation time of charges due to random factors, such as proficiency of operators, environmental parameters, etc. Such deviation is called operation time delay which includes starting time delay and completion time delay according the different time points.

2.2.1. Starting Time Delay

As one of raw materials for converters, molten irons of high temperature are transported by torpedo car from the blast furnace to the steelmaking plant and are poured into the ladles, and are finally poured into converters from ladles. During the transportation, molten irons need to be processed by the former slag, desulfurization, posterior slag. In those processes, the actual starting time of charges will be often later than the initial starting time because of proficiency of operators, environmental parameters, etc.

The production scheduling in SMCC production process mainly considers main equipment (converters, refining furnaces, and continuous casting machines). But in the actual production process, incoordination between the scheduling of auxiliary equipment and the scheduling of main equipment will result that crane and trolley can not be in place in time, which leads to starting time delay at refining stage.

We denote the s_{ijk}^* for the actual starting time of operation o_{ijk} . If s_{ijk}^* is later than the initial starting time s_{ijk}^0 ,

$$s_{ijk}^* > s_{ijk}^0 \dots\dots\dots (1)$$

then starting time delay disturbance occurs. The Δt indicates the time delay, and $\Delta t = s_{ijk}^* - s_{ijk}^0$.

2.2.2. Completion Time Delay

Due to a variety of random factors, such as the impact of machine failure, the proficiency of the operation of workers, environmental parameters, etc, it is hard to get accurate processing time and can only get an approximate data or data range for processing time of the molten steel in the equipment. In the actual production process, the processing time of charge is closely related to the molten steel temperature and components. With the changes of these factors, the actual processing time is also changing and is often different from initial processing time.

We denote the e_{ijk}^* for the actual completion time of the operation o_{ijk} . If e_{ijk}^* is later than the initial completion time e_{ijk}^0 ,

$$e_{ijk}^* > e_{ijk}^0 \dots\dots\dots (2)$$

then completion time delay disturbance occurs. The Δt indicates the time delay, and $\Delta t = e_{ijk}^* - e_{ijk}^0$.

2.3. Classification in Abnormal Conditions of Scheduling Plan in SMCC Production Process

Abnormal conditions of scheduling plan in SMCC production process mainly include planned casting break and processing conflict.

(1) Planned casting break

Casting break means that continuous caster can not pull out the slab through the mold because of a variety of reasons

which results that continuous casting process is interrupted. In this paper, we divide casting break into “unplanned casting break” and “planned casting break”. Unplanned casting break is that molten steel can not enter the mold for condensation because of nozzle clogging for low temperature of molten steel, nozzle clogging of ladle, nozzle clogging of tundish, etc. Unplanned casting break actually occurs in the production process. The following preventive measures can be adopted to reduce the number of occurrences of unplanned casting break: improving qualified rate of molten steel temperature in tundish, improving the cleanliness of molten steel, calcium treatment in molten steel, and etc. Planned casting break is that other factors affects the initial scheduling plan which results that some molten steel can not reach steel ladle turret in time according to initial scheduling plan and continuous casting is interrupted in the future because of molten steel supply interruption. Planned casting break is not what actually happened in the production process. It means that some factors, such as operation time delay, affect the initial scheduling plan, and if production is still going on according to the initial scheduling plan, then casting break will happen in the future.

If planned casting break occurs between charge $L_{i,j-1}$ and L_{ij} , then abnormal conditions of scheduling plan can be divided into the following four conditions:

■ **One-level planned casting break.** It can resolve the planned casting break between charge $L_{i,j-1}$ and L_{ij} only by adjusting the processing time of $L_{i,j-1}$ at continuous casting stage, or only by adjusting the processing time of L_{ij} at each stage.

■ **Two-level planned casting break.** It can not resolve the planned casting break between charge $L_{i,j-1}$ and L_{ij} only by adjusting the processing time of $L_{i,j-1}$ at continuous casting stage, or only by adjusting the processing time of L_{ij} at each stage. But the planned casting break between charge $L_{i,j-1}$ and L_{ij} can be resolved synchronously by adjusting the processing time of $L_{i,j-1}$ at continuous casting stage and the processing time of L_{ij} at each stage.

■ **Three-level planned casting break.** It can not resolve the planned casting break between charge $L_{i,j-1}$ and L_{ij} synchronously by adjusting the processing time of $L_{i,j-1}$ at continuous casting stage and the processing time of L_{ij} at each stage. But the planned casting break between charge $L_{i,j-1}$ and L_{ij} can be resolved synchronously by adjusting the processing time of L_{ij_1} ($j_1 \leq j$) at each stage.

■ **Four-level planned casting break.** It can not resolve the planned casting break between charge $L_{i,j-1}$ and L_{ij} synchronously by adjusting the processing time of L_{ij_1} ($j_1 \leq j$) at each stage. But the planned casting break between charge $L_{i,j-1}$ and L_{ij} can be resolved synchronously by adjusting the processing machines of L_{ij_1} ($j_1 \leq j$) at steelmaking stage and at refining stage, and by adjusting the processing time of L_{ij_1} ($j_1 \leq j$) at each stage.

(2) Processing conflict

SMCC process is a non-preemptive processing, which means that when one operation is being processed on the machine, other operations are prohibited to preempt the same machine. Once one operation begins to be processed, it is not allowed to interrupt until the processing finishes. If processing conflict occurs between charge L_{i,j_1} and L_{i,j_2} on machine m_{gb} , then abnormal conditions of processing conflict can be divided into the following five conditions:

■ **One-level processing conflict.** It can resolve the processing conflict between charge L_{i,j_1} and L_{i,j_2} only by adjusting the processing time of L_{i,j_1} on machine m_{gb} , or only by adjusting the processing time of L_{i,j_2} on machine m_{gb} .

■ **Two-level processing conflict.** It can not resolve the processing conflict between charge L_{i,j_1} and L_{i,j_2} only by

adjusting the processing time of L_{i,j_1} on machine m_{gb} , or only by adjusting the processing time of L_{i,j_2} on machine m_{gb} . But the processing conflict between charge L_{i,j_1} and L_{i,j_2} can be resolved synchronously by adjusting the processing time of L_{i,j_1} and L_{i,j_2} .

■ **Three-level processing conflict.** It can not resolve the processing conflict between charge L_{i,j_1} and L_{i,j_2} synchronously by adjusting the processing time of L_{i,j_1} and L_{i,j_2} on machine m_{gb} . But the processing conflict between charge L_{i,j_1} and L_{i,j_2} can be resolved synchronously by adjusting the processing time of L_{i,j_1} and L_{i,j_2} on each stage.

■ **Four-level processing conflict.** It can not resolve the processing conflict between charge L_{i,j_1} and L_{i,j_2} synchronously by adjusting the processing time of L_{i,j_1} and L_{i,j_2} on each stage. But the processing conflict between charge L_{i,j_1} and L_{i,j_2} can be resolved synchronously by adjusting the processing time of L_{i,j_1} , L_{i,j_2} and other charges on each stage.

■ **Five-level processing conflict.** It can not resolve the processing conflict between charge L_{i,j_1} and L_{i,j_2} synchronously by adjusting the processing time of L_{i,j_1} , L_{i,j_2} and other charges on each stage. But the processing conflict between charge L_{i,j_1} and L_{i,j_2} may be resolved synchronously by adjusting the processing machines and processing time of L_{i,j_1} , L_{i,j_2} and other charges on each stage.

3. Prediction Strategy for Abnormal Condition of Scheduling Plan with Operation Time Delay Disturbance in SMCC Production Process

A four-stage prediction strategy for abnormal condition of scheduling plan with operation time delay disturbance in SMCC production process is proposed as shown in Fig. 1, which includes: disturbance identification of operating time delay based on event-driven mechanism, analysis on charges based on reachability matrix, analysis on influence degree of disturbance and abnormal condition decision of initial scheduling plan.

(1) Disturbance identification of operating time delay based on event-driven mechanism

Disturbance identification of operating time delay based on event-driven mechanism compares the actual starting time s_{ijk}^* and the initial starting time s_{ijk}^0 , or compares the actual completion time e_{ijk}^* and the initial completion time e_{ijk}^0 according to the actual starting time s_{ijk}^* or the actual completion time e_{ijk}^* . It can obtain the disturbance identification result according to the comparison result, which is denoted as Y , and $Y = \{o, m, y, \tau\}$. The o is defined as the charge with operating time disturbance. The m denotes the machine on which disturbance occurs. The τ indicates disturbance value. We define the y as the disturbance type, $y \in \{y_0, y_1, y_2, y_3, y_4\}$. The y_0 represents that there is no disturbance occurs. The y_1 represents that starting time delay occurs on the converter. The y_2 represents that completion time delay occurs on the converter. The y_3 represents that starting time delay occurs on the refining furnace. The y_4 represents that

Fig. 1. Prediction strategy for abnormal condition of scheduling plan with operation time delay disturbance in SMCC production process.

completion time delay occurs on the refining furnace.

(2) Analysis on charges based on reachability matrix

Analysis on charges based on reachability matrix is to analyze the charges which are affected by the disturbance identification result Y according to the initial processing machine z_{ijk}^0 , the initial starting time s_{ijk}^0 and the initial completion time e_{ijk}^0 . The O denotes those charges set.

(3) Analysis on influence degree of disturbance

Analysis on influence degree of disturbance analyzes the influence degree of disturbance on charges from O according to the disturbance identification result Y , initial scheduling plan S^0 , the minimum processing time $p_{ijk}^{\min}$, the standard processing time p_{ijk}^{nor} , the maximum processing time $p_{ijk}^{\max}$, the transportation time $u(m_{g_1b_1}, m_{g_2b_2})$ between machine $m_{g_1b_1}$ and machine $m_{g_2b_2}$. We define T as the influence degree result.

(4) Abnormal condition decision of initial scheduling plan

Abnormal condition decision of initial scheduling plan predicts the abnormal condition according to the influence degree result T . The H indicates the abnormal condition result, and $H = \{m, o_1, o_2, \zeta\}$. The m denotes the machine on which disturbance occurs. The o_1 and o_2 indicate operations with disturbance, respectively. We define the ζ as the abnormal condition type, and $\zeta \in \{\zeta_{11}, \zeta_{12}, \zeta_{13}, \zeta_{14}, \zeta_{21}, \zeta_{22}, \zeta_{23}, \zeta_{24}, \zeta_{25}\}$. The ζ_{11} , ζ_{12} , ζ_{13} and ζ_{14} denote one-level planned casting break, two-level planned casting break, three-level planned casting break and four-level planned casting break, respectively. The ζ_{21} , ζ_{22} , ζ_{23} , ζ_{24} and ζ_{25} represent one-level processing conflict, two-level processing conflict, three-level processing conflict, four-level processing conflict and five-level processing conflict, respectively.

4. A Novel Prediction Method for Abnormal Condition of Scheduling Plan with Operation Time Delay Disturbance in SMCC Production Process

4.1. Disturbance Identification of Operating Time Delay Based on Event-driven Mechanism

In the SMCC production process, once the operation is being processed or finished, dynamic event information collected from actual production includes the machine code m , operation o , processing status type χ , occurrence time of processing status t . If processing status is starting, then $\chi = 1$. If processing status has been finished, then $\chi = 2$. Disturbance identification model is established according above dynamic event information as follows:

$$Y = f(m, o, \chi, t, s_{ijk}^0, e_{ijk}^0 | o_{ijk} \in O) \dots\dots\dots (3)$$

where O denotes the unfinished operations set. The s_{ijk}^0 and e_{ijk}^0 indicate the initial starting time and the initial completion time of operation o_{ijk} from O , respectively. If operation o_{ijk} is not processed, then $\delta_{ijk}^1 = 0$. If operation o_{ijk} is being processed, then $\delta_{ijk}^1 = 1$. If operation o_{ijk} has not finished being processed, then $\delta_{ijk}^2 = 0$. If operation o_{ijk} has been processed, then $\delta_{ijk}^2 = 1$. The disturbance identification algorithm of operating time delay based on event-driven mechanism is described in detail as follows:

Step1: Initialize the scheduling information: $S^0 = \{z_{ijk}^0, s_{ijk}^0, e_{ijk}^0 | o_{ijk} \in L_{ij}, L_{ij} \in \Omega\}$, where Ω is the set of unfinished casting charges.

Step2: Initialize the operations processing status: $\forall o_{ijk} \in O$, $\delta_{ijk}^1 = 0$, $\delta_{ijk}^2 = 0$.

Step3: If event occurs, then get event information: machine code m , operation o , processing status type χ , occurrence time of processing status t . Select the operation o_{i,j,k_1} from O which o_{i,j,k_1} is equal to operation o . If $\chi = 1$, then go to the next step, else go to Step5.

Step4: Let $\delta_{i,j,k_1}^1 = 1$, $s_{i,j,k_1}^* = t$, $\tau = s_{i,j,k_1}^* - s_{i,j,k_1}^0$. If $\tau = 0$, then

$y = y_0$. If $k = 1$, $\tau > 0$, then $y = y_1$. If $1 < k < \theta_{ij}$, $\tau > 0$ then $y = y_3$.

Step5: Let $\delta_{i,j,k_1}^2 = 1$, $e_{i,j,k_1}^* = t$, $\tau = e_{i,j,k_1}^* - e_{i,j,k_1}^0$. If $\tau = 0$, then $y = y_0$. If $k = 1$, $\tau > 0$, then $y = y_2$. If $1 < k < \theta_{ij}$, $\tau > 0$, then $y = y_4$.

Step6: Get the final disturbance identification result Y , and $Y = \{o, m, y, \tau\}$.

4.2. Analysis on Charges Based on Reachability Matrix

In the SMCC production, it must have been processed on the former operation o_{ijk} and then it can be processed on the next operation $o_{i,j,k+1}$ for each charge. The adjacent charges in the same machine must be processed one by one. So, when operation time delay of one operation occurs, it will affects other operations and scheduling performance, even make the initial scheduling plan become unrealizable. It firstly needs to analyze the charges which are affected by the disturbance identification in order to analyze the influence degree of disturbances to the initial scheduling plan S^0 . The working status of each machine is divided into idle, processing the first operation or middle operation of one charge and processing the last operation of one charge. We define the $\square$, $\bigcirc$, $\triangle$ as those three status, respectively. The interval time between adjacent operations from the same charge is the sum of the transportation time and waiting time, which is indicated as ellipse. The scheduling plan including two charges is as shown in Fig. 2(a). $L_{11} = \{o_{111}, o_{112}, o_{113}\}$ and $L_{12} = \{o_{121}, o_{122}, o_{123}\}$. Operations of each charge are processed by 1LD, 1RH and 1CC. The time constraints relationship between operations of charge L_{11} and L_{12} is shown in Fig. 2(b). The node 2 and node 4 denote operation o_{111} and operation o_{121} on machine 1LD, respectively. The node 8 and node 10 denote operation o_{112} and operation o_{122} on machine 1RH, respectively. The node 14 and node 15 denote operation o_{113} and operation o_{123} on machine 1CC, respectively. The node 5 denotes the interval time between operation o_{111} and operation o_{112} . The node 6 denotes the interval time between operation o_{121} and operation o_{122} . The node 11 and node 12 denote the interval time between operation o_{112} and operation o_{113} and the interval time between operation o_{122} and operation o_{123} , respectively. The nodes 1, 3, 7, 9, 13 indicate the idle time.

The arrows between operations indicate the influence direction of operating time delay as shown in Fig. 2(b). For example, the arrows between operations on the same machine represent that the operating time delay of former operation will cause the operating time delay of the subsequent other operation. The arrows between operations on the different machine denote that the operating time delay of former operation will cause the operating time delay of the subsequent operation from the same charge.

Fig. 2. The time constraints relationship between operations of charges.

The reachability matrix R , which reflects the system node connectivity in graph theory, is introduced to represent the interaction relationship between operations in order to analyze the influence degree of disturbances to the initial scheduling plan S^0 . R can be obtained by the adjacency matrix C which indicates the adjacency relationship of nodes. The adjacency matrix C is defined as follows:

$$C = \|c_{l_1 l_2}\| \quad l_1, l_2 = 1, \dots, N \quad (4)$$

where l_1 and l_2 denote the nodes, respectively. N indicates the total number of nodes. If node l_1 and node l_2 are adjacent, and the arrow points to the node l_2 from the node l_1 , then $c_{l_1 l_2} = 1$, else $c_{l_1 l_2} = 0$. For example, the adjacency matrix C in Fig. 2(b) is as follows:

$$C = \begin{bmatrix} & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 & 11 & 12 & 13 & 14 & 15 \\ 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 2 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 3 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 4 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 5 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 6 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 7 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 8 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 \\ 9 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 10 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 11 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 12 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 13 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 14 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 15 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \quad (5)$$

The reachability matrix R can be obtained by the adjacency matrix C as follows:

$$R = \|r_{l_1 l_2}\| \quad l_1, l_2 = 1, \dots, N \quad (6)$$

If there exists directed path from the node l_1 to the node l_2 , then $r_{l_1 l_2} = 1$, else $r_{l_1 l_2} = 0$. When one node l task represented by $\bigcirc$ in Fig. 2(b) delays, it will only make other node task delay which is connected with the node l and does not make other node task delay which is not connected with the node l . It can clearly identify the operations which are affected by operation time delay by the reachability matrix. The reachability matrix in Fig. 2(b) is as follows:

$$R = \begin{bmatrix} & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 & 11 & 12 & 13 & 14 & 15 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 1 & 1 & 1 & 1 & 1 & 0 & 1 & 1 \\ 2 & 0 & 1 & 1 & 1 & 1 & 1 & 0 & 1 & 1 & 1 & 1 & 1 & 0 & 1 & 1 \\ 3 & 0 & 0 & 1 & 1 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 1 \\ 4 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 1 \\ 5 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 1 & 1 & 1 & 1 & 1 & 0 & 1 & 1 \\ 6 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 1 \\ 7 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 1 & 1 \\ 8 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 & 0 & 1 & 1 \\ 9 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 1 & 0 & 0 & 1 \\ 10 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 1 \\ 11 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 1 & 1 \\ 12 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 1 \\ 13 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 \\ 14 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 \\ 15 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \quad (7)$$

4.3. Analysis on Influence Degree of Disturbance

4.3.1. Analysis on Processing Conflict Caused by Operation Time Delay

It can find all operations which are affected by operation time delay by the reachability matrix. When node l delays Δt minutes, then the node which is connected with the node l will also delay Δt minutes.

When the starting time of the node l_0 denoting the operation o_{ijk_1} delays Δt minutes, that is $\Delta t = s_{ijk_1}^* - s_{ijk_1}^0$, recalculate the starting time s_{ijk_1} and the completion time e_{ijk_1} of the operation o_{ijk_1} as follows:

$$s_{ijk_1} = s_{ijk_1}^* = s_{ijk_1}^0 + \Delta t \quad (8)$$

$$e_{ijk_1} = s_{ijk_1} + p_{ijk_1}^0 = e_{ijk_1}^0 + \Delta t \quad (9)$$

where $p_{ijk_1}^0$ is the processing time of operation o_{ijk_1} in the initial scheduling plan. When the completion time of the node l_0 delays Δt minutes, that is $\Delta t = e_{ijk_1}^* - e_{ijk_1}^0$, recalculate the starting time s_{ijk_1} and the completion time e_{ijk_1} of the operation o_{ijk_1} as follows:

$$s_{ijk_1} = s_{ijk_1}^0 \quad (10)$$

$$e_{ijk_1} = e_{ijk_1}^0 + \Delta t \quad (11)$$

The new starting time s_{ijk} and the new completion time e_{ijk} of the subsequent operations of o_{ijk_1} are recalculated as follows:

$$s_{ijk} = e_{i,j,k-1} + u(z_{i,j,k-1}^0, z_{ijk}^0) \quad k = k_1 + 1, \dots, \theta_{ij} \quad (12)$$

$$e_{ijk} = s_{ijk} + p_{ijk}^0 \quad k = k_1 + 1, \dots, \theta_{ij} \quad (13)$$

where $z_{i,j,k-1}^0$ and z_{ijk}^0 are the processing machine of the operation $o_{i,j,k-1}$ and the processing machine of the operation o_{ijk} , respectively. The $u(z_{i,j,k-1}^0, z_{ijk}^0)$ is the standard transportation time between $o_{i,j,k-1}$ and o_{ijk} . We define the $o_{l(ijk)}$ as the subsequent operation of the operation o_{ijk} on machine z_{ijk}^0 . The $\chi_{l(ijk)}^{ijk}$ denotes the processing conflict time as follows:

$$\chi_{l(ijk)}^{ijk} = \min(e_{ijk}, e_{l(ijk)}^0) - \max(s_{ijk}, s_{l(ijk)}^0) \quad k = k_1, \dots, \theta_{ij} \quad (14)$$

The formula (14) can be rewritten as follows according to the formula (8) to formula (13):

$$\chi_{l(ijk)}^{ijk} = \min \left(e_{ijk} + \sum_{k_2=k_1}^k p_{ijk_2}^0 + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0), e_{l(ijk)}^0 \right) - \max \left(s_{ijk_1} + \sum_{k_2=k_1}^{k-1} p_{ijk_2}^0 + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0), s_{l(ijk)}^0 \right) \quad k = k_1, \dots, \theta_{ij} \quad (15)$$

The formula (15) is the relational model between the processing conflict time between operation o_{ijk} and other operation o_{ijk} ($k = k_1, \dots, \theta_{ij}$) and the operation delay time Δt of operation o_{ijk_1} when the operation delay time of o_{ijk_1} is Δt . If $\chi_{l(ijk)}^{ijk} \leq 0$, then the processing conflict does not occur. If $\chi_{l(ijk)}^{ijk} > 0$, then the processing conflict occurs and the conflict time is $\chi_{l(ijk)}^{ijk}$.

4.3.2. Analysis on Planned Casting Break Caused by Operation Time Delay

When the delay time of operation o_{ijk_1} is Δt , then the new starting time of $o_{i,j,\theta_{ij}}$ can be recalculated as follows according to the formula (8) to formula (13):

$$s_{i,j,\theta_{ij}} = e_{ijk_1}^0 + \Delta t + \sum_{k_2=k_1+1}^{\theta_{ij}-1} p_{ijk_2}^0 + \sum_{k_3=k_1}^{\theta_{ij}-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0) \quad (16)$$

We define $\gamma_{j-1,j}^i$ as the planned casting break time between charge $L_{i,j-1}$ and charge L_{ij} :

$$\gamma_{j-1,j}^i = s_{i,j,\theta_j} - e_{i,j-1,\theta_{i,j-1}}^0 \quad (17)$$

The formula (17) can be rewritten as follows according to the formula (16):

$$\gamma_{j-1,j}^i = e_{ijk_1}^0 + \Delta t + \sum_{k_2=k_1+1}^{\theta_j-1} p_{ijk_2}^0 + \sum_{k_3=k_1}^{\theta_j-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0) - e_{i,j-1,\theta_{i,j-1}}^0 \quad (18)$$

The formula (18) is the relational model between the planned casting break time and the operation delay time Δt of operation o_{ijk_1} when the operation delay time of o_{ijk_1} is Δt . If $\gamma_{j-1,j}^i \leq 0$, then the planned casting break does not occur. If $\gamma_{j-1,j}^i > 0$, then the planned casting break occurs and the planned casting break time is $\gamma_{j-1,j}^i$.

4.3.3. Buffer Units of Scheduling System in SMCC Production Process

When the operation delay time of o_{ijk_1} is Δt , we can obtain the processing conflict time and the planned casting break time according to the formula (15) and (18). If the node l_0 has the buffer function, then the operation time delay of the subsequent connected node can be reduced through the buffer function. Supposing that the buffer time of the node l_0 is T , then the operation time delay of the subsequent connected node is $\Delta t - T$. If $\Delta t - T < 0$, then the operation time of the subsequent connected node will not delay. When the operation delay time of node l_1 is Δt , the buffer units of scheduling system in SMCC production process are as follows:

(1) *The idle time on machines.* If the node l_1 connects to the node of the idle time, then the node of the idle time will play the role of time compensation. Supposing that the idle time is T , then the operation time delay of the subsequent connected node is $\Delta t - T$. If $\Delta t - T < 0$, then the operation time of the subsequent connected node will not delay.

(2) *Adjustment range of processing time of charge on the machine.* We can only get a range of processing time of operations because the processing time of operations is affected by randomness. The processing time includes the minimum processing time $p_{ijk}^{\min}$, the standard processing time p_{ijk}^{nor} , the maximum processing time $p_{ijk}^{\max}$. The processing time of operation o_{ijk} can be adjusted in $[p_{ijk}^{\min}, p_{ijk}^{\max}]$. Supposing that the processing time of o_{ijk} in the initial scheduling plan is p_{ijk}^0 . If $\Delta t - (p_{ijk}^0 - p_{ijk}^{\min}) < 0$, then the operation time of the subsequent connected node will not delay.

(3) *The interval time between adjacent operations of the same charge.* SMCC process is a non-preemptive processing, which means that when one operation is being processed on the machine, other operations are prohibited to preempt the same machine. Once one operation begins to be processed, it is not allowed to interrupt until the processing finishes. If the interval time between adjacent operations of the same charge includes the waiting time, then it has the buffer function. Supposing that the interval time between o_{ijk} and $o_{i,j,k+1}$ is $u_{ijk}^0(z_{ijk}^0, z_{i,j,k+1}^0)$. If $\Delta t - (u_{ijk}^0(z_{ijk}^0, z_{i,j,k+1}^0) - u_{ijk}^0(z_{i,j,k+1}^0, z_{i,j,k+1}^0)) < 0$, then the operation time of the subsequent connected node will not delay.

The buffer matrix is defined as follows according to the above analysis:

$$E = \|\varepsilon_l\| \quad l = 1, \dots, N \quad (19)$$

where ε_l denotes the buffer time of the node l .

(1) If the node l is the node of the idle time T , then

$$\varepsilon_l = T \quad (20)$$

(2) If the node l indicates the operation o_{ijk} of the charge, then

$$\varepsilon_l = p_{ijk}^0 - p_{ijk}^{\min} \quad (21)$$

(3) If the node l denotes the interval time between adjacent operations of the same charge, then

$$\varepsilon_l = u^0(z_{ijk}^0, z_{i,j,k+1}^0) - u(z_{ijk}^0, z_{i,j,k+1}^0) \quad (22)$$

where $u^0(z_{ijk}^0, z_{i,j,k+1}^0)$ is the interval time between o_{ijk} and $o_{i,j,k+1}$, and $u(z_{ijk}^0, z_{i,j,k+1}^0)$ is the standard transportation time between o_{ijk} and $o_{i,j,k+1}$.

If $\varepsilon_l > 0$ in the buffer matrix E , it means that the node l has the buffer time. The operation time delay of the subsequent connected node can be reduced through the buffer time. If the operation delay time of the node l is Δt , then the operation time delay of the subsequent connected node can be reduced to $\Delta t - \varepsilon_l$. If $\varepsilon_l = 0$, then the operation time delay of the subsequent connected node will also be Δt .

It can be known that we can obtain the processing conflict time and the planned casting break time according to the formula (15) and (18) when the operation delay time of o_{ijk_1} is Δt . If there have buffer units, then the processing conflict time and the planned casting break time can not be directly obtained according to the formula (15) and formula (18). These are closely related with the buffer units. So, it is needed to deeply analyze the relationship between delay time Δt and buffer units in order to find out the really impact on the scheduling system by delay time Δt .

4.3.4. Analysis on Influence Degree of Disturbance by Operation Time Delay under Buffer Units

When the operation delay time of o_{ijk_1} is Δt , the analysis model of the impact on the starting time of operations by operation time delay under buffer units is established as follows according to the reachability matrix R and the buffer matrix E :

$$T_1(l_0, \Delta t) = \|\eta_l\| \quad l = 1, \dots, N \quad (23)$$

where the η_l denotes the final delay time of the starting time of the node l affected by the delay time Δt of the node l_0 . If $r_{l_0 l} = 0$, then $\eta_l = 0$. If $r_{l_0 l} = 1$ and there exists $B(B \geq 1)$ directed paths from the node l_0 to the node l , then the η_l is equal to the maximum delay time of the starting time of all nodes in the directed paths:

$$\eta_l = \max_{b=1, \dots, B} \left(\Delta t - \sum_{\substack{l_1 \in P_b(l_0, l) \\ l_1 \neq l}} \sum_{\substack{l_2 \in P_b(l_0, l) \\ l_2 \neq l}} c_{l_1 l_2} \varepsilon_{l_1} \right) \quad r_{l_0 l} = 1 \quad (24)$$

where $P_b(l_0, l)$ is the b th directed path in B directed paths.

The analysis model of the impact on the completion time of operations by operation time delay under buffer units is established as follows according to the formula (19) and the formula (23):

$$T_2(l_0, \Delta t) = \|\lambda_l\| \quad l = 1, \dots, N \quad (25)$$

where the λ_l indicates the final delay time of the completion time of the node l affected by the delay time Δt of the node l_0 . If $r_{l_0 l} = 0$, then $\lambda_l = 0$. If $r_{l_0 l} = 1$, then $\lambda_l = \eta_l - \varepsilon_l$.

According to the above analysis, the analysis model of the processing conflict time between adjacent operations is established as follows when the operation delay time is Δt :

$$\tilde{\chi}_{l(ijk)}^{ijk} = \min(e_{ijk}^0 + \lambda_{l_1} \cdot e_{l(ijk)}^0 + \lambda_{l_2}) - \max(s_{ijk}^0 + \eta_{l_1}, s_{l(ijk)}^0 + \eta_{l_2}) \quad (26)$$

where the o_{ijk_1} is the corresponding operation for the node l_0 , the o_{ijk} is the corresponding operation for the node l_1 and the $o_{l(ijk)}$ is the corresponding operation for the node l_2 . If $\tilde{\chi}_{l(ijk)}^{ijk} \leq 0$, then there is no processing conflict time between o_{ijk} and $o_{l(ijk)}$ through the buffer units. If $\tilde{\chi}_{l(ijk)}^{ijk} > 0$, it means that there is still processing conflict time between o_{ijk} and

$o_{l(jk)}$ through the buffer units.

The analysis model of the planned casting break time between adjacent charges in the same cast is established as follows when the operation delay time is Δt :

$$\tilde{\gamma}_{j-1,j}^i = (s_{i,j,\theta_{ij}}^0 + \eta_{l_2}) - (e_{i,j-1,\theta_{i,j-1}}^0 + \lambda_{l_1}) = \eta_{l_2} - \lambda_{l_1} \dots (27)$$

where the $o_{i,j,\theta_{ij}}$ is the corresponding operation for the node l_2 and the $o_{i,j-1,\theta_{i,j-1}}$ is the corresponding operation for the node l_1 . If $\tilde{\gamma}_{j-1,j}^i \leq 0$, there is no planned casting break time between $o_{i,j-1,\theta_{i,j-1}}$ and $o_{i,j,\theta_{ij}}$ through the buffer units. If $\tilde{\gamma}_{j-1,j}^i > 0$, there is still planned casting break time between $o_{i,j-1,\theta_{i,j-1}}$ and $o_{i,j,\theta_{ij}}$ through the buffer units.

4.4. Abnormal Condition Decision of Initial Scheduling Plan

The formula (26) and the formula (27) denote the final the processing conflict time and the final planned casting break time under buffer units, respectively. The processing conflict time and the planned casting break time are resolved by under buffer units in fact, which is the adjustment method. The different abnormal condition of the scheduling plan by the operation time delay can lead to the different adjustment method to resolve the abnormal condition. So, prediction for abnormal condition of scheduling plan with operation time delay disturbance in SMCC production process is very important.

4.4.1. The Planned Casting Break Decision of Initial Scheduling Plan by Operation Time Delay under Buffer Units

The G denotes the time constraint graph between operations. The V indicates the all nodes set in G . When the node l_0 (l_0 is correspond to the charge L_{ij}) delay Δt , if $\gamma_{j-1,j}^i > 0$, then there is planned casting break time between $L_{i,j-1}$ and L_{ij} . The $o_{i,j-1,\theta_{i,j-1}}$ is the corresponding operation for the node l_1 and the $o_{i,j,\theta_{ij}}$ is the corresponding operation for the node l_2 . We define the V_{ij} as the all nodes set for charge L_{ij} . The planned casting break decision is made as follows:

(1) If $p_{i,j-1,\theta_{i,j-1}}^{\max} - p_{i,j-1,\theta_{i,j-1}}^0 - \gamma_{j-1,j}^i \geq 0$, then the abnormal condition of scheduling plan is one-level planned casting break ζ_{11} .

Proof. When the node l_0 (l_0 is correspond to operation o_{ijk_1} the charge L_{ij}) delay Δt , according to the formula (18),

$$\gamma_{j-1,j}^i = e_{ijk_1}^0 + \Delta t + \sum_{k_2=k_1+1}^{\theta_{ij}-1} p_{ijk_2}^0 + \sum_{k_3=k_1}^{\theta_{ij}-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0) - e_{i,j-1,\theta_{i,j-1}}^0 \cdot e_{i,j-1,\theta_{i,j-1}}^0 \text{ is}$$

the initial completion time of operation $o_{i,j-1,\theta_{i,j-1}}$ and the initial processing time of operation $o_{i,j-1,\theta_{i,j-1}}$ is $p_{i,j-1,\theta_{i,j-1}}^0$. If the processing time of operation $o_{i,j-1,\theta_{i,j-1}}$ is adjusted to $p_{i,j-1,\theta_{i,j-1}}^{\max}$, then the new completion time $e_{i,j-1,\theta_{i,j-1}}$ of operation $o_{i,j-1,\theta_{i,j-1}}$ can be recalculated as follows: $e_{i,j-1,\theta_{i,j-1}} = e_{i,j-1,\theta_{i,j-1}}^0 + p_{i,j-1,\theta_{i,j-1}}^{\max} - p_{i,j-1,\theta_{i,j-1}}^0$. Then according to the formula (18), the new planned casting break time (denoted as $(\gamma_{j-1,j}^i)'$) can be recalculated as follows:

$$\begin{aligned} (\gamma_{j-1,j}^i)' &= e_{ijk_1}^0 + \Delta t + \sum_{k_2=k_1+1}^{\theta_{ij}-1} p_{ijk_2}^0 + \sum_{k_3=k_1}^{\theta_{ij}-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0) - e_{i,j-1,\theta_{i,j-1}}^0 \\ &= e_{ijk_1}^0 + \Delta t + \sum_{k_2=k_1+1}^{\theta_{ij}-1} p_{ijk_2}^0 + \sum_{k_3=k_1}^{\theta_{ij}-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0) - e_{i,j-1,\theta_{i,j-1}}^0 \\ &\quad - p_{i,j-1,\theta_{i,j-1}}^{\max} + p_{i,j-1,\theta_{i,j-1}}^0 \\ &= \gamma_{j-1,j}^i - p_{i,j-1,\theta_{i,j-1}}^{\max} + p_{i,j-1,\theta_{i,j-1}}^0 \dots (28) \end{aligned}$$

If $p_{i,j-1,\theta_{i,j-1}}^{\max} - p_{i,j-1,\theta_{i,j-1}}^0 - \gamma_{j-1,j}^i \geq 0$, then $(\gamma_{j-1,j}^i)' \leq 0$. It can be seen that the planned casting break between $o_{i,j-1,\theta_{i,j-1}}$ and $o_{i,j,\theta_{ij}}$ can be resolved only by adjusting the processing time of $L_{i,j-1}$ at continuous casting stage. So, according to the

classification of planned casting break of scheduling plan (section 2.3), the abnormal condition is one-level planned casting break ζ_{11} .

(2) If $p_{i,j-1,\theta_{i,j-1}}^{\max} - p_{i,j-1,\theta_{i,j-1}}^0 - \gamma_{j-1,j}^i < 0$, then for the nodes $l|l \in V, l \notin V_{ij}$, let $\varepsilon_l = 0$. If $\tilde{\gamma}_{j-1,j}^i \leq 0$, then the abnormal condition of scheduling plan is one-level planned casting break ζ_{11} .

Proof. If $p_{i,j-1,\theta_{i,j-1}}^{\max} - p_{i,j-1,\theta_{i,j-1}}^0 - \gamma_{j-1,j}^i < 0$, then $(\gamma_{j-1,j}^i)' > 0$ according to the formula (28). It can be seen that the planned casting break between $o_{i,j-1,\theta_{i,j-1}}$ and $o_{i,j,\theta_{ij}}$ can not be resolved only by adjusting the processing time of $L_{i,j-1}$ at continuous casting stage. For the nodes $l|l \in V, l \notin V_{ij}$, let $\varepsilon_l = 0$, which means that only nodes belonging to V_{ij} have buffer time. According to the formula (27), $\tilde{\gamma}_{j-1,j}^i = (s_{i,j,\theta_{ij}}^0 + \eta_{l_2}) - (e_{i,j-1,\theta_{i,j-1}}^0 + \lambda_{l_1}) = \eta_{l_2} - \lambda_{l_1}$. If $\tilde{\gamma}_{j-1,j}^i \leq 0$, then It can be seen that the planned casting break between $o_{i,j-1,\theta_{i,j-1}}$ and $o_{i,j,\theta_{ij}}$ can be resolved only by adjusting the processing time of L_{ij} at each stage. So, according to the classification of planned casting break of scheduling plan (section 2.3), the abnormal condition is one-level planned casting break ζ_{11} .

(3) If $p_{i,j-1,\theta_{i,j-1}}^{\max} - p_{i,j-1,\theta_{i,j-1}}^0 - \gamma_{j-1,j}^i < 0$, then for the nodes $l|l \in V, l \notin V_{ij}$, let $\varepsilon_l = 0$. If $\tilde{\gamma}_{j-1,j}^i > 0$, but $p_{i,j-1,\theta_{i,j-1}}^{\max} - p_{i,j-1,\theta_{i,j-1}}^0 - \tilde{\gamma}_{j-1,j}^i \geq 0$, then the abnormal condition of scheduling plan is two-level planned casting break ζ_{12} .

Proof. If $p_{i,j-1,\theta_{i,j-1}}^{\max} - p_{i,j-1,\theta_{i,j-1}}^0 - \gamma_{j-1,j}^i < 0$, then $(\gamma_{j-1,j}^i)' > 0$, it can be seen that the planned casting break between $o_{i,j-1,\theta_{i,j-1}}$ and $o_{i,j,\theta_{ij}}$ can not be resolved only by adjusting the processing time of $L_{i,j-1}$ at continuous casting stage. For the nodes $l|l \in V, l \notin V_{ij}$, let $\varepsilon_l = 0$. According to the formula (27), $\tilde{\gamma}_{j-1,j}^i = (s_{i,j,\theta_{ij}}^0 + \eta_{l_2}) - (e_{i,j-1,\theta_{i,j-1}}^0 + \lambda_{l_1}) = \eta_{l_2} - \lambda_{l_1}$. If $\tilde{\gamma}_{j-1,j}^i > 0$, then It can be seen that the planned casting break between $o_{i,j-1,\theta_{i,j-1}}$ and $o_{i,j,\theta_{ij}}$ can not be resolved only by adjusting the processing time of L_{ij} at each stage. If the processing time of operation $o_{i,j-1,\theta_{i,j-1}}$ is adjusted to $p_{i,j-1,\theta_{i,j-1}}^{\max}$, then the new completion time $e_{i,j-1,\theta_{i,j-1}}$ of operation $o_{i,j-1,\theta_{i,j-1}}$ can be recalculated as follows: $e_{i,j-1,\theta_{i,j-1}} = e_{i,j-1,\theta_{i,j-1}}^0 + p_{i,j-1,\theta_{i,j-1}}^{\max} - p_{i,j-1,\theta_{i,j-1}}^0$. Then according to the formula (27), the new planned casting break time (denoted as $(\tilde{\gamma}_{j-1,j}^i)'$) can be recalculated as follows:

$$\begin{aligned} (\tilde{\gamma}_{j-1,j}^i)' &= (s_{i,j,\theta_{ij}}^0 + \eta_{l_2}) - (e_{i,j-1,\theta_{i,j-1}}^0 + \lambda_{l_1}) \\ &= (s_{i,j,\theta_{ij}}^0 + \eta_{l_2}) - (e_{i,j-1,\theta_{i,j-1}}^0 + p_{i,j-1,\theta_{i,j-1}}^{\max} - p_{i,j-1,\theta_{i,j-1}}^0 + \lambda_{l_1}) \\ &= (s_{i,j,\theta_{ij}}^0 + \eta_{l_2}) - (e_{i,j-1,\theta_{i,j-1}}^0 + \lambda_{l_1}) - p_{i,j-1,\theta_{i,j-1}}^{\max} + p_{i,j-1,\theta_{i,j-1}}^0 \\ &= \tilde{\gamma}_{j-1,j}^i - p_{i,j-1,\theta_{i,j-1}}^{\max} + p_{i,j-1,\theta_{i,j-1}}^0 \dots (29) \end{aligned}$$

If $p_{i,j-1,\theta_{i,j-1}}^{\max} - p_{i,j-1,\theta_{i,j-1}}^0 - \tilde{\gamma}_{j-1,j}^i \geq 0$, then $(\tilde{\gamma}_{j-1,j}^i)' \leq 0$. It can be seen that the planned casting break between $o_{i,j-1,\theta_{i,j-1}}$ and $o_{i,j,\theta_{ij}}$ can be resolved synchronously by adjusting the processing time of $L_{i,j-1}$ at continuous casting stage and the processing time of L_{ij} at each stage. So, according to the classification of planned casting break of scheduling plan (section 2.3), the abnormal condition is two-level planned casting break ζ_{12} .

(4) If let $\varepsilon_l = 0$ for the nodes $l|l \in V, l \notin V_{ij}$, $p_{i,j-1,\theta_{i,j-1}}^{\max} - p_{i,j-1,\theta_{i,j-1}}^0 - \gamma_{j-1,j}^i < 0$, $\tilde{\gamma}_{j-1,j}^i > 0$, $p_{i,j-1,\theta_{i,j-1}}^{\max} - p_{i,j-1,\theta_{i,j-1}}^0 - \tilde{\gamma}_{j-1,j}^i < 0$. If let $\varepsilon_l \neq 0$ for the nodes $l|l \in V, \tilde{\gamma}_{j-1,j}^i \leq 0$, then the abnormal condition of scheduling plan is three-level planned casting break ζ_{13} .

Proof. For the nodes $l|l \in V, l \notin V_{ij}$, let $\varepsilon_l = 0$. If $p_{i,j-1,\theta_{i,j-1}}^{\max} - p_{i,j-1,\theta_{i,j-1}}^0 - \gamma_{j-1,j}^i < 0$, $\tilde{\gamma}_{j-1,j}^i > 0$, $p_{i,j-1,\theta_{i,j-1}}^{\max} - p_{i,j-1,\theta_{i,j-1}}^0 - \tilde{\gamma}_{j-1,j}^i < 0$, it means that the planned casting break between $o_{i,j-1,\theta_{i,j-1}}$ and $o_{i,j,\theta_{ij}}$ can not be resolved synchronously by adjusting the processing time of $L_{i,j-1}$ at continuous casting stage and the processing time of L_{ij} at each stage according to the above analysis. If let $\varepsilon_l \neq 0$ for the nodes $l|l \in V$, then all nodes have duffer time. If $\tilde{\gamma}_{j-1,j}^i \leq 0$, then it means that the planned casting break between charge $L_{i,j-1}$ and L_{ij} can be resolved syn-

chronously by adjusting the processing time of $L_{ij}(j_1 \leq j)$ at each stage. So, according to the classification of planned casting break of scheduling plan (section 2.3), the abnormal condition is three-level planned casting break ζ_{13} .

(5) For the nodes $l|l \in V$, if $\tilde{\gamma}_{j-1,j}^i > 0$, then the abnormal condition of scheduling plan is four-level planned casting break ζ_{14} .

Proof. If let $\varepsilon_l \neq 0$ for the nodes $l|l \in V$, then all nodes have dufer time. If $\tilde{\gamma}_{j-1,j}^i > 0$, then it can be known that the planned casting break between charge $L_{i,j-1}$ and L_{ij} can not be resolved synchronously by adjusting the processing time of $L_{ij}(j_1 \leq j)$ at each stage according to the above analysis. In this case, the planned casting break must be resolved synchronously by adjusting the processing machines of $L_{ij}(j_1 \leq j)$ at steelmaking stage and refining stage and by adjusting the processing time of $L_{ij}(j_1 \leq j)$ at each stage. So, according to the classification of planned casting break of scheduling plan (section 2.3), the abnormal condition is four-level planned casting break ζ_{14} .

4.4.2. The Processing Conflict Decision of Initial Scheduling Plan by Operation Time Delay under Buffer Units

When the node l_0 (l_0 is correspond to the charge L_{ij}) delay Δt , if $\chi_{l(ijk)}^{ijk} > 0$, then there is processing conflict time between o_{ijk} and $o_{l(ijk)}$. The o_{ijk} is the corresponding operation for the node l_1 and the $o_{l(ijk)}$ is the corresponding operation for the node l_2 . We define the V_1 as the all nodes set for charge L_{ij} and the V_2 as the all nodes set for charge including $o_{l(ijk)}$. The processing conflict decision is made as follows:

(1) If $\varepsilon_{l_1} - \chi_{l(ijk)}^{ijk} \geq 0$, then the abnormal condition of scheduling plan is one-level processing conflict ζ_{21} .

Proof. The operation $o_{l(ijk)}$ is the subsequent operation of the operation o_{ijk} on machine in the initial scheduling plan. When the operation time delay occurs, the processing conflict time $\chi_{l(ijk)}^{ijk}$ can be calculated according to the formula (15). According to the new processing sequence between o_{ijk} and $o_{l(ijk)}$, the processing conflict can be divided into two cases.

■ Case 1: o_{ijk} is also processed before $o_{l(ijk)}$ in the new scheduling plan. In this case, the completion time of o_{ijk} is earlier than the completion time of $o_{l(ijk)}$ which means $e_{ijk} < e_{l(ijk)}^0$. So,

it can be known that $e_{ijk_1} + \sum_{k_2=k_1+1}^k p_{ijk_2}^0 + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0) < e_{l(ijk)}^0$.

The processing conflict between o_{ijk} and $o_{l(ijk)}$ may be resolved by adjusting the processing time of o_{ijk} . According to the formula (21), $\varepsilon_{l_1} = p_{ijk}^0 - p_{ijk}^{\min}$. If the starting time of operation o_{ijk} is not changed and the processing time of o_{ijk} is adjusted to $p_{ijk}^{\min}$, then according to the formula (15), the new processing conflict time (denoted as $(\chi_{l(ijk)}^{ijk})'$) can be recalculated as follows ($k = k_1, \dots, \theta_{ij}$):

$$\begin{aligned} (\chi_{l(ijk)}^{ijk})' &= \min \left(e_{ijk_1} + \sum_{k_2=k_1+1}^{k-1} p_{ijk_2}^0 + p_{ijk}^{\min} + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0), e_{l(ijk)}^0 \right) \\ &\quad - \max \left(s_{ijk_1} + \sum_{k_2=k_1}^{k-1} p_{ijk_2}^0 + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0), s_{l(ijk)}^0 \right) \\ &= \min \left(e_{ijk_1} + \sum_{k_2=k_1+1}^{k-1} p_{ijk_2}^0 + p_{ijk}^{\min} - \varepsilon_{l_1} + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0), e_{l(ijk)}^0 \right) \\ &\quad - \max \left(s_{ijk_1} + \sum_{k_2=k_1}^{k-1} p_{ijk_2}^0 + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0), s_{l(ijk)}^0 \right) \end{aligned} \quad (30)$$

Because $e_{ijk_1} + \sum_{k_2=k_1+1}^k p_{ijk_2}^0 + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0) < e_{l(ijk)}^0$, $e_{ijk_1} + \sum_{k_2=k_1+1}^k$

$p_{ijk_2}^0 + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0) - \varepsilon_{l_1} < e_{l(ijk)}^0$. So the minimum value of first term in the formula (30) is $e_{ijk_1} + \sum_{k_2=k_1+1}^{k-1} p_{ijk_2}^0 + p_{ijk}^{\min} - \varepsilon_{l_1} + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0)$. Then the formula (30) can be rewritten as follows:

$$\begin{aligned} (\chi_{l(ijk)}^{ijk})' &= \left(\min \left(e_{ijk_1} + \sum_{k_2=k_1+1}^k p_{ijk_2}^0 + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0), e_{l(ijk)}^0 \right) - \varepsilon_{l_1} \right) \\ &\quad - \max \left(s_{ijk_1} + \sum_{k_2=k_1}^{k-1} p_{ijk_2}^0 + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0), s_{l(ijk)}^0 \right) \\ &= \min \left(e_{ijk_1} + \sum_{k_2=k_1+1}^k p_{ijk_2}^0 + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0), e_{l(ijk)}^0 \right) \\ &\quad - \max \left(s_{ijk_1} + \sum_{k_2=k_1}^{k-1} p_{ijk_2}^0 + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0), s_{l(ijk)}^0 \right) - \varepsilon_{l_1} \\ &= \chi_{l(ijk)}^{ijk} - \varepsilon_{l_1} \end{aligned} \quad (31)$$

If $\varepsilon_{l_1} - \chi_{l(ijk)}^{ijk} \geq 0$, then $(\chi_{l(ijk)}^{ijk})' \leq 0$. It can resolve the processing conflict between o_{ijk} and $o_{l(ijk)}$ only by adjusting the processing time of o_{ijk} . So, according to the classification of processing conflict of scheduling plan (section 2.3), the abnormal condition is one-level processing conflict ζ_{21} .

■ Case 2: o_{ijk} is processed after $o_{l(ijk)}$ in the new scheduling plan. In this case, the starting time of o_{ijk} is later than the starting time of $o_{l(ijk)}$ which means $s_{ijk} > s_{l(ijk)}^0$. So, it can be

known that $s_{ijk_1} + \sum_{k_2=k_1}^{k-1} p_{ijk_2}^0 + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0) > s_{l(ijk)}^0$. According to

the formula (21), $\varepsilon_{l_1} = p_{ijk}^0 - p_{ijk}^{\min}$. If the completion time of operation o_{ijk} is not changed and the processing time of o_{ijk} is adjusted to $p_{ijk}^{\min}$, then according to the formula (15), the new processing conflict time (denoted as $(\chi_{l(ijk)}^{ijk})'$) can be recalculated as follows ($k = k_1, \dots, \theta_{ij}$):

$$\begin{aligned} (\chi_{l(ijk)}^{ijk})' &= \min \left(e_{ijk_1} + \sum_{k_2=k_1+1}^k p_{ijk_2}^0 + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0), e_{l(ijk)}^0 \right) \\ &\quad - \max \left(s_{ijk_1} + \sum_{k_2=k_1}^{k-1} p_{ijk_2}^0 + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0) + \varepsilon_{l_1}, s_{l(ijk)}^0 \right) \end{aligned} \quad (32)$$

Because $s_{ijk_1} + \sum_{k_2=k_1}^{k-1} p_{ijk_2}^0 + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0) > s_{l(ijk)}^0$, $s_{ijk_1} + \sum_{k_2=k_1}^{k-1} p_{ijk_2}^0 + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0) + \varepsilon_{l_1} > s_{l(ijk)}^0$. So the maximum value of second

term in the formula (32) is $s_{ijk_1} + \sum_{k_2=k_1}^{k-1} p_{ijk_2}^0 + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0) + \varepsilon_{l_1}$. Then the formula (32) can be rewritten as follows:

$$\begin{aligned} (\chi_{l(ijk)}^{ijk})' &= \min \left(e_{ijk_1} + \sum_{k_2=k_1+1}^k p_{ijk_2}^0 + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0), e_{l(ijk)}^0 \right) \\ &\quad - \left(\max \left(s_{ijk_1} + \sum_{k_2=k_1}^{k-1} p_{ijk_2}^0 + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0), s_{l(ijk)}^0 \right) + \varepsilon_{l_1} \right) \\ &= \min \left(e_{ijk_1} + \sum_{k_2=k_1+1}^k p_{ijk_2}^0 + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0), e_{l(ijk)}^0 \right) \end{aligned}$$

$$\begin{aligned}
 & -\max \left(s_{ijk_1} + \sum_{k_2=k_1}^{k-1} p_{ijk_2}^0 + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0), s_{l(ijk)}^0 \right) - \varepsilon_{l_1} \\
 & = \chi_{l(ijk)}^{ijk} - \varepsilon_{l_1}
 \end{aligned}
 \tag{33}$$

If $\varepsilon_{l_1} - \chi_{l(ijk)}^{ijk} \geq 0$, then $(\chi_{l(ijk)}^{ijk})' \leq 0$. It can resolve the processing conflict between o_{ijk} and $o_{l(ijk)}$ only by adjusting the processing time of o_{ijk} . So, according to the classification of processing conflict of scheduling plan (section 2.3), the abnormal condition is one-level processing conflict ζ_{21} .

To sum up, if $\varepsilon_{l_1} - \chi_{l(ijk)}^{ijk} \geq 0$, then the abnormal condition of scheduling plan is one-level processing conflict ζ_{21} .

(2) If $\varepsilon_{l_2} - \chi_{l(ijk)}^{ijk} \geq 0$, then the abnormal condition of scheduling plan is one-level processing conflict ζ_{21} .

Proof. The operation $o_{l(ijk)}$ is the subsequent operation of the operation o_{ijk} on machine in the initial scheduling plan. When the operation time delay occurs, the processing conflict time $\chi_{l(ijk)}^{ijk}$ can be calculated according to the formula (15). According to the new processing sequence between o_{ijk} and $o_{l(ijk)}$, the processing conflict can be divided into two cases.

■ Case 1: o_{ijk} is also processed before $o_{l(ijk)}$ in the new scheduling plan. In this case, the starting time of $o_{l(ijk)}$ is later than the starting time of o_{ijk} which means $s_{l(ijk)}^0 > s_{ijk}$. So, it

can be known that $s_{l(ijk)}^0 > s_{ijk_1} + \sum_{k_2=k_1}^{k-1} p_{ijk_2}^0 + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0)$.

The processing conflict between o_{ijk} and $o_{l(ijk)}$ may be resolved by adjusting the processing time of $o_{l(ijk)}$. According to the formula (21), $\varepsilon_{l_2} = p_{l(ijk)}^0 - p_{l(ijk)}^{\min}$. If the completion time of operation $o_{l(ijk)}$ is not changed and the processing time of $o_{l(ijk)}$ is adjusted to $p_{l(ijk)}^{\min}$, then according to the formula (15), the new processing conflict time (denoted as $(\chi_{l(ijk)}^{ijk})'$) can be recalculated as follows ($k = k_1, \dots, \theta_{ij}$):

$$\begin{aligned}
 & (\chi_{l(ijk)}^{ijk})' = \min \left(e_{ijk_1} + \sum_{k_2=k_1+1}^k p_{ijk_2}^0 + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0), e_{l(ijk)}^0 \right) \\
 & - \max \left(s_{ijk_1} + \sum_{k_2=k_1}^{k-1} p_{ijk_2}^0 + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0), s_{l(ijk)}^0 + \varepsilon_{l_2} \right) \dots (34)
 \end{aligned}$$

Because $s_{l(ijk)}^0 > s_{ijk_1} + \sum_{k_2=k_1}^{k-1} p_{ijk_2}^0 + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0)$, $s_{l(ijk)}^0 + \varepsilon_{l_2} >$

$s_{ijk_1} + \sum_{k_2=k_1}^{k-1} p_{ijk_2}^0 + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0)$. So the maximum value of second term in the formula (34) is $s_{l(ijk)}^0 + \varepsilon_{l_2}$. Then the formula (34) can be rewritten as follows:

$$\begin{aligned}
 & (\chi_{l(ijk)}^{ijk})' = \min \left(e_{ijk_1} + \sum_{k_2=k_1+1}^k p_{ijk_2}^0 + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0), e_{l(ijk)}^0 \right) \\
 & - \left(\max \left(s_{ijk_1} + \sum_{k_2=k_1}^{k-1} p_{ijk_2}^0 + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0), s_{l(ijk)}^0 \right) + \varepsilon_{l_2} \right) \\
 & = \min \left(e_{ijk_1} + \sum_{k_2=k_1+1}^k p_{ijk_2}^0 + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0), e_{l(ijk)}^0 \right) \\
 & - \max \left(s_{ijk_1} + \sum_{k_2=k_1}^{k-1} p_{ijk_2}^0 + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0), s_{l(ijk)}^0 \right) - \varepsilon_{l_2} \\
 & = \chi_{l(ijk)}^{ijk} - \varepsilon_{l_2}
 \end{aligned}
 \tag{35}$$

If $\varepsilon_{l_2} - \chi_{l(ijk)}^{ijk} \geq 0$, then $(\chi_{l(ijk)}^{ijk})' \leq 0$. It can resolve the process-

ing conflict between o_{ijk} and $o_{l(ijk)}$ only by adjusting the processing time of $o_{l(ijk)}$. So, according to the classification of processing conflict of scheduling plan (section 2.3), the abnormal condition is one-level processing conflict ζ_{21} .

■ Case 2: o_{ijk} is processed after $o_{l(ijk)}$ in the new scheduling plan. In this case, the completion time of $o_{l(ijk)}$ is earlier than the completion time of o_{ijk} which means $e_{l(ijk)}^0 < e_{ijk}$. So,

it can be known that $e_{l(ijk)}^0 < e_{ijk_1} + \sum_{k_2=k_1+1}^k p_{ijk_2}^0 + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0)$.

The processing conflict between o_{ijk} and $o_{l(ijk)}$ may be resolved by adjusting the processing time of $o_{l(ijk)}$. According to the formula (21), $\varepsilon_{l_2} = p_{l(ijk)}^0 - p_{l(ijk)}^{\min}$. If the starting time of operation $o_{l(ijk)}$ is not changed and the processing time of $o_{l(ijk)}$ is adjusted to $p_{l(ijk)}^{\min}$, then according to the formula (15), the new processing conflict time (denoted as $(\chi_{l(ijk)}^{ijk})'$) can be recalculated as follows ($k = k_1, \dots, \theta_{ij}$):

$$\begin{aligned}
 & (\chi_{l(ijk)}^{ijk})' = \min \left(e_{ijk_1} + \sum_{k_2=k_1+1}^k p_{ijk_2}^0 + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0), e_{l(ijk)}^0 - \varepsilon_{l_2} \right) \\
 & - \max \left(s_{ijk_1} + \sum_{k_2=k_1}^{k-1} p_{ijk_2}^0 + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0), s_{l(ijk)}^0 \right)
 \end{aligned}
 \tag{36}$$

Because $e_{l(ijk)}^0 < e_{ijk_1} + \sum_{k_2=k_1+1}^k p_{ijk_2}^0 + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0)$, $e_{l(ijk)}^0 - \varepsilon_{l_2} <$

$e_{ijk_1} + \sum_{k_2=k_1+1}^k p_{ijk_2}^0 + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0)$. So the minimum value of first term in the formula (36) is $e_{l(ijk)}^0 - \varepsilon_{l_2}$. Then the formula (36) can be rewritten as follows:

$$\begin{aligned}
 & (\chi_{l(ijk)}^{ijk})' = \min \left(e_{ijk_1} + \sum_{k_2=k_1+1}^k p_{ijk_2}^0 + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0), e_{l(ijk)}^0 - \varepsilon_{l_2} \right) \\
 & - \max \left(s_{ijk_1} + \sum_{k_2=k_1}^{k-1} p_{ijk_2}^0 + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0), s_{l(ijk)}^0 \right) \\
 & = \min \left(e_{ijk_1} + \sum_{k_2=k_1+1}^k p_{ijk_2}^0 + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0), e_{l(ijk)}^0 \right) \\
 & - \max \left(s_{ijk_1} + \sum_{k_2=k_1}^{k-1} p_{ijk_2}^0 + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0), s_{l(ijk)}^0 \right) - \varepsilon_{l_2} \\
 & = \chi_{l(ijk)}^{ijk} - \varepsilon_{l_2}
 \end{aligned}
 \tag{37}$$

If $\varepsilon_{l_2} - \chi_{l(ijk)}^{ijk} \geq 0$, then $(\chi_{l(ijk)}^{ijk})' \leq 0$. It can resolve the processing conflict between o_{ijk} and $o_{l(ijk)}$ only by adjusting the processing time of $o_{l(ijk)}$. So, according to the classification of processing conflict of scheduling plan (section 2.3), the abnormal condition is one-level processing conflict ζ_{21} .

To sum up, if $\varepsilon_{l_2} - \chi_{l(ijk)}^{ijk} \geq 0$, then the abnormal condition of scheduling plan is one-level processing conflict ζ_{21} .

(3) If $\varepsilon_{l_1} - \chi_{l(ijk)}^{ijk} < 0$, $\varepsilon_{l_2} - \chi_{l(ijk)}^{ijk} < 0$, $\varepsilon_{l_1} + \varepsilon_{l_2} - \chi_{l(ijk)}^{ijk} \geq 0$, then the abnormal condition of scheduling plan is two-level processing conflict ζ_{22} .

Proof. The operation $o_{l(ijk)}$ is the subsequent operation of the operation o_{ijk} on machine in the initial scheduling plan. When the operation time delay occurs, the processing conflict time $\chi_{l(ijk)}^{ijk}$ can be calculated according to the formula (15). According to above analysis, if $\varepsilon_{l_1} - \chi_{l(ijk)}^{ijk} < 0$, it can not resolve the processing conflict between o_{ijk} and $o_{l(ijk)}$ only by adjusting the processing time of o_{ijk} . If $\varepsilon_{l_2} - \chi_{l(ijk)}^{ijk} < 0$, it can not resolve the processing conflict between o_{ijk} and $o_{l(ijk)}$ only by adjusting the processing time of $o_{l(ijk)}$. According to the new processing sequence between o_{ijk} and $o_{l(ijk)}$, the processing conflict can be divided into two cases.

■ Case 1: o_{ijk} is also processed before $o_{l(ijk)}$ in the new sched-

uling plan. In this case, the completion time of o_{ijk} is earlier than the completion time of $o_{l(ijk)}$ which means $e_{ijk} < e_{l(ijk)}^0$. So,

it can be known that $e_{ijk_1} + \sum_{k_2=k_1+1}^k p_{ijk_2}^0 + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0) < e_{l(ijk)}^0$.

The starting time of $o_{l(ijk)}$ is later than the starting time of o_{ijk} which means $s_{l(ijk)}^0 > s_{ijk}^0$. So, it can be known that $s_{l(ijk)}^0 >$

$s_{ijk_1} + \sum_{k_2=k_1}^{k-1} p_{ijk_2}^0 + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0)$. The processing conflict may

be resolved synchronously by adjusting the processing time of o_{ijk} and $o_{l(ijk)}$. According to the formula (21), $\varepsilon_{l_1} = p_{ijk}^0 - p_{ijk}^{\min}$ and $\varepsilon_{l_2} = p_{l(ijk)}^0 - p_{l(ijk)}^{\min}$. If the starting time of operation o_{ijk} is not changed and the processing time of o_{ijk} is adjusted to, and if the completion time of operation $o_{l(ijk)}$ is not changed and the processing time of $o_{l(ijk)}$ is adjusted to $p_{l(ijk)}^{\min}$, then according to the formula (15), the new processing conflict time (denoted as $(\chi_{l(ijk)}^{ijk})'$) can be recalculated as follows ($k = k_1, \dots, \theta_{ij}$):

$$\begin{aligned} & (\chi_{l(ijk)}^{ijk})' \\ &= \min \left(e_{ijk_1} + \sum_{k_2=k_1+1}^{k-1} p_{ijk_2}^0 + p_{ijk}^0 - \varepsilon_{l_1} + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0), e_{l(ijk)}^0 \right) \\ & - \max \left(s_{ijk_1} + \sum_{k_2=k_1}^{k-1} p_{ijk_2}^0 + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0), s_{l(ijk)}^0 + \varepsilon_{l_2} \right) \quad \dots (38) \end{aligned}$$

Because $e_{ijk_1} + \sum_{k_2=k_1+1}^k p_{ijk_2}^0 + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0) < e_{l(ijk)}^0$ and $s_{l(ijk)}^0 >$
 $s_{ijk_1} + \sum_{k_2=k_1}^{k-1} p_{ijk_2}^0 + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0)$, $e_{ijk_1} + \sum_{k_2=k_1+1}^k p_{ijk_2}^0 + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0) -$
 $\varepsilon_{l_1} < e_{l(ijk)}^0$ and $s_{l(ijk)}^0 + \varepsilon_{l_2} > s_{ijk_1} + \sum_{k_2=k_1}^{k-1} p_{ijk_2}^0 + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0)$. Then
 the formula (38) can be rewritten as follows:

$$\begin{aligned} & (\chi_{l(ijk)}^{ijk})' = \left(\min \left(e_{ijk_1} + \sum_{k_2=k_1+1}^{k-1} p_{ijk_2}^0 + p_{ijk}^0 + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0), e_{l(ijk)}^0 \right) - \varepsilon_{l_1} \right) \\ & - \left(\max \left(s_{ijk_1} + \sum_{k_2=k_1}^{k-1} p_{ijk_2}^0 + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0), s_{l(ijk)}^0 \right) + \varepsilon_{l_2} \right) \\ &= \min \left(e_{ijk_1} + \sum_{k_2=k_1+1}^{k-1} p_{ijk_2}^0 + p_{ijk}^0 + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0), e_{l(ijk)}^0 \right) \\ & - \max \left(s_{ijk_1} + \sum_{k_2=k_1}^{k-1} p_{ijk_2}^0 + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0), s_{l(ijk)}^0 \right) - \varepsilon_{l_1} - \varepsilon_{l_2} \\ &= \chi_{l(ijk)}^{ijk} - \varepsilon_{l_1} - \varepsilon_{l_2} \quad \dots (39) \end{aligned}$$

If $\varepsilon_{l_1} + \varepsilon_{l_2} - \chi_{l(ijk)}^{ijk} \geq 0$, then $(\chi_{l(ijk)}^{ijk})' \leq 0$. It can resolve the processing conflict between o_{ijk} and $o_{l(ijk)}$ synchronously by adjusting the processing time of o_{ijk} and $o_{l(ijk)}$. So, according to the classification of processing conflict of scheduling plan (section 2.3), the abnormal condition is one-level processing conflict ζ_{22} .

■ Case 2: o_{ijk} is processed after $o_{l(ijk)}$ in the new scheduling

plan. It can be known that $s_{ijk_1} + \sum_{k_2=k_1}^{k-1} p_{ijk_2}^0 + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0) >$

$s_{l(ijk)}^0$ and $e_{l(ijk)}^0 < e_{ijk_1} + \sum_{k_2=k_1+1}^k p_{ijk_2}^0 + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0)$. If the com-

pletion time of operation o_{ijk} is not changed and the processing time of o_{ijk} is adjusted to $p_{ijk}^{\min}$, and if the starting time of operation $o_{l(ijk)}$ is not changed and the processing time of

$o_{l(ijk)}$ is adjusted to $p_{l(ijk)}^{\min}$, then according to the formula (15), the new processing conflict time (denoted as $(\chi_{l(ijk)}^{ijk})'$) can be recalculated as follows ($k = k_1, \dots, \theta_{ij}$):

$$\begin{aligned} & (\chi_{l(ijk)}^{ijk})' = \min \left(e_{ijk_1} + \sum_{k_2=k_1+1}^k p_{ijk_2}^0 + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0), e_{l(ijk)}^0 - \varepsilon_{l_2} \right) \\ & - \max \left(s_{ijk_1} + \sum_{k_2=k_1}^{k-1} p_{ijk_2}^0 + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0) + \varepsilon_{l_1}, s_{l(ijk)}^0 \right) \quad \dots (40) \end{aligned}$$

Because $e_{l(ijk)}^0 < e_{ijk_1} + \sum_{k_2=k_1+1}^k p_{ijk_2}^0 + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0)$ and $s_{ijk_1} +$
 $\sum_{k_2=k_1}^{k-1} p_{ijk_2}^0 + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0) > s_{l(ijk)}^0$, $e_{l(ijk)}^0 - \varepsilon_{l_2} < e_{ijk_1} + \sum_{k_2=k_1+1}^k p_{ijk_2}^0 +$
 $\sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0)$ and $s_{ijk_1} + \sum_{k_2=k_1}^{k-1} p_{ijk_2}^0 + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0) + \varepsilon_{l_1} > s_{l(ijk)}^0$.

Then the formula (40) can be rewritten as follows:

$$\begin{aligned} & (\chi_{l(ijk)}^{ijk})' = \left(\min \left(e_{ijk_1} + \sum_{k_2=k_1+1}^k p_{ijk_2}^0 + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0), e_{l(ijk)}^0 \right) - \varepsilon_{l_2} \right) \\ & - \left(\max \left(s_{ijk_1} + \sum_{k_2=k_1}^{k-1} p_{ijk_2}^0 + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0), s_{l(ijk)}^0 \right) + \varepsilon_{l_1} \right) \\ &= \min \left(e_{ijk_1} + \sum_{k_2=k_1+1}^k p_{ijk_2}^0 + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0), e_{l(ijk)}^0 \right) \\ & - \max \left(s_{ijk_1} + \sum_{k_2=k_1}^{k-1} p_{ijk_2}^0 + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0), s_{l(ijk)}^0 \right) - \varepsilon_{l_1} - \varepsilon_{l_2} \\ &= \chi_{l(ijk)}^{ijk} - \varepsilon_{l_1} - \varepsilon_{l_2} \quad \dots (41) \end{aligned}$$

If $\varepsilon_{l_1} + \varepsilon_{l_2} - \chi_{l(ijk)}^{ijk} \geq 0$, then $(\chi_{l(ijk)}^{ijk})' \leq 0$. It can resolve the processing conflict between o_{ijk} and $o_{l(ijk)}$ synchronously by adjusting the processing time of o_{ijk} and $o_{l(ijk)}$. So, according to the classification of processing conflict of scheduling plan (section 2.3), the abnormal condition is one-level processing conflict ζ_{22} .

To sum up, If $\varepsilon_{l_1} - \chi_{l(ijk)}^{ijk} < 0$, $\varepsilon_{l_2} - \chi_{l(ijk)}^{ijk} < 0$, $\varepsilon_{l_1} + \varepsilon_{l_2} - \chi_{l(ijk)}^{ijk} \geq 0$, then the abnormal condition of scheduling plan is two-level processing conflict ζ_{22} .

(4) If $\varepsilon_{l_1} + \varepsilon_{l_2} - \chi_{l(ijk)}^{ijk} < 0$, then let $\varepsilon_l = 0$ for the nodes $l | l \in V, l \notin V_1, l \notin V_2$. If $\sum_{l_i \in V_1^*} \varepsilon_{l_i} + \sum_{l_i \in V_2^*} \varepsilon_{l_i} - \chi_{l(ijk)}^{ijk} \geq 0$, then the abnormal

condition of scheduling plan is three-level processing conflict ζ_{23} .

Proof. According to above analysis, if $\varepsilon_{l_1} + \varepsilon_{l_2} - \chi_{l(ijk)}^{ijk} < 0$, It can not resolve the processing conflict between o_{ijk} and $o_{l(ijk)}$ synchronously by adjusting the processing time of o_{ijk} and $o_{l(ijk)}$. We define $o_{l(ijk)}$ is the k^1 th operation of the charge L_{i^1,j^1} , so the $o_{l(ijk)}$ can also be denoted as o_{i^1,j^1,k^1} . We define the V_1^* as the all nodes set for $o_{ijk_1} | k_1^* \leq k$ of L_{i^1,j^1} and the V_2^* as the all nodes set for $o_{i^1,j^1,k_2^*} | k_2^* \leq k^1$ of L_{i^1,j^1} . The processing conflict may be resolved synchronously by adjusting the processing time of operations in V_1^* and V_2^* . According to the new processing sequence between o_{ijk} and $o_{l(ijk)}$, the processing conflict can be divided into two cases.

■ Case 1: o_{ijk} is also processed before $o_{l(ijk)}$ in the new

scheduling plan. It can be known that $e_{ijk_1} + \sum_{k_2=k_1+1}^k p_{ijk_2}^0 +$

$\sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0) < e_{l(ijk)}^0$ and $s_{l(ijk)}^0 > s_{ijk_1} + \sum_{k_2=k_1}^{k-1} p_{ijk_2}^0 + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0)$.

If the starting time of o_{ijk_1} is not changed, the processing time of operation o_{ijk_1} in V_1^* is adjusted to $p_{ijk_1}^{\min}$, the earliest starting time of operation in V_2^* is not changed, the processing time of operation o_{ijk_2} in $V_2^* - \{o_{ijk_1}\}$ is adjusted to $p_{ijk_2}^{\max}$, and the processing time of operation o_{ijk_3} is adjusted to $p_{ijk_3}^{\min}$, the processing conflict may be resolved. According to the formula (15), the new processing conflict time (denoted as $(\chi_{I(ijk)}^{ijk})$) can be recalculated as follows ($k = k_1, \dots, \theta_j$):

$$\begin{aligned} & (\chi_{I(ijk)}^{ijk}) \\ &= \min \left(e_{ijk_1} + \sum_{k_2=k_1+1}^k p_{ijk_2}^0 - \sum_{l'_1 \in V_1^*} \varepsilon_{l'_1} + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0) \cdot e_{I(ijk)}^0 + \sum_{l'_2 \in V_2^* - \{o_{ijk_1}\}} \varepsilon_{l'_2} \right) \\ & \quad - \max \left(s_{ijk_1} + \sum_{k_2=k_1}^{k-1} p_{ijk_2}^0 - \sum_{l'_1 \in V_1^* - \{o_{ijk_1}\}} \varepsilon_{l'_1} + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0) \cdot s_{I(ijk)}^0 + \sum_{l'_2 \in V_2^*} \varepsilon_{l'_2} \right) \end{aligned} \quad (42)$$

Because $e_{ijk_1} + \sum_{k_2=k_1+1}^k p_{ijk_2}^0 + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0) < e_{I(ijk)}^0$ and $s_{I(ijk)}^0 > s_{ijk_1} + \sum_{k_2=k_1}^{k-1} p_{ijk_2}^0 + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0)$, $e_{ijk_1} + \sum_{k_2=k_1+1}^k p_{ijk_2}^0 - \sum_{l'_1 \in V_1^*} \varepsilon_{l'_1} + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0) < e_{I(ijk)}^0 + \sum_{l'_2 \in V_2^* - \{o_{ijk_1}\}} \varepsilon_{l'_2}$ and $s_{I(ijk)}^0 + \sum_{l'_2 \in V_2^*} \varepsilon_{l'_2} > s_{ijk_1} + \sum_{k_2=k_1}^{k-1} p_{ijk_2}^0 - \sum_{l'_1 \in V_1^* - \{o_{ijk_1}\}} \varepsilon_{l'_1} + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0)$. Then the formula (42) can be rewritten as follows:

$$\begin{aligned} & (\chi_{I(ijk)}^{ijk}) = \left(\min \left(e_{ijk_1} + \sum_{k_2=k_1+1}^k p_{ijk_2}^0 + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0) \cdot e_{I(ijk)}^0 + \sum_{l'_2 \in V_2^* - \{o_{ijk_1}\}} \varepsilon_{l'_2} \right) - \sum_{l'_1 \in V_1^*} \varepsilon_{l'_1} \right) \\ & \quad - \left(\max \left(s_{ijk_1} + \sum_{k_2=k_1}^{k-1} p_{ijk_2}^0 - \sum_{l'_1 \in V_1^* - \{o_{ijk_1}\}} \varepsilon_{l'_1} + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0) \cdot s_{I(ijk)}^0 + \sum_{l'_2 \in V_2^*} \varepsilon_{l'_2} \right) \right) \\ &= \min \left(e_{ijk_1} + \sum_{k_2=k_1+1}^k p_{ijk_2}^0 + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0) \cdot e_{I(ijk)}^0 + \sum_{l'_2 \in V_2^* - \{o_{ijk_1}\}} \varepsilon_{l'_2} \right) \\ & \quad - \max \left(s_{ijk_1} + \sum_{k_2=k_1}^{k-1} p_{ijk_2}^0 - \sum_{l'_1 \in V_1^* - \{o_{ijk_1}\}} \varepsilon_{l'_1} + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0) \cdot s_{I(ijk)}^0 + \sum_{l'_2 \in V_2^*} \varepsilon_{l'_2} \right) \\ &= \min \left(e_{ijk_1} + \sum_{k_2=k_1+1}^k p_{ijk_2}^0 + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0) \cdot e_{I(ijk)}^0 \right) \\ & \quad - \max \left(s_{ijk_1} + \sum_{k_2=k_1}^{k-1} p_{ijk_2}^0 + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0) \cdot s_{I(ijk)}^0 \right) - \sum_{l'_1 \in V_1^*} \varepsilon_{l'_1} - \sum_{l'_2 \in V_2^*} \varepsilon_{l'_2} \\ &= \chi_{I(ijk)}^{ijk} - \sum_{l'_1 \in V_1^*} \varepsilon_{l'_1} - \sum_{l'_2 \in V_2^*} \varepsilon_{l'_2} \end{aligned} \quad (43)$$

If $\sum_{l'_1 \in V_1^*} \varepsilon_{l'_1} + \sum_{l'_2 \in V_2^*} \varepsilon_{l'_2} - \chi_{I(ijk)}^{ijk} \geq 0$, then $(\chi_{I(ijk)}^{ijk})' \leq 0$. It can resolve

the processing conflict between o_{ijk} and $o_{I(ijk)}$ synchronously by adjusting the processing time of operations of L_{ij} and charge L_{ij}^{ij} . So, according to the classification of processing conflict of scheduling plan (section 2.3), the abnormal condition is three-level processing conflict ζ_{23} .

■ Case 2: o_{ijk} is processed after $o_{I(ijk)}$ in the new scheduling

plan. It can be known that $s_{ijk_1} + \sum_{k_2=k_1}^{k-1} p_{ijk_2}^0 + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0) > s_{I(ijk)}^0$

and $e_{I(ijk)}^0 < e_{ijk_1} + \sum_{k_2=k_1+1}^k p_{ijk_2}^0 + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0)$. If the starting time

of o_{ijk_1} is not changed, the processing time of operation o_{ijk_1} in $V_1^* - \{o_{ijk_1}\}$ is adjusted to $p_{ijk_1}^{\max}$, the processing time of oper-

ation o_{ijk} is adjusted to $p_{ijk}^{\min}$, the earliest starting time of operation in V_2^* is not changed, the processing time of operation o_{ijk_2} in V_2^* is adjusted to $p_{ijk_2}^{\min}$, the processing conflict may be resolved. According to the formula (15), the new processing conflict time (denoted as $(\chi_{I(ijk)}^{ijk})$) can be recalculated as follows ($k = k_1, \dots, \theta_j$):

$$\begin{aligned} & (\chi_{I(ijk)}^{ijk}) \\ &= \min \left(e_{ijk_1} + \sum_{k_2=k_1+1}^k p_{ijk_2}^0 + \sum_{l'_1 \in V_1^* - \{o_{ijk_1}\}} \varepsilon_{l'_1} + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0) \cdot e_{I(ijk)}^0 - \sum_{l'_2 \in V_2^*} \varepsilon_{l'_2} \right) \\ & \quad - \max \left(s_{ijk_1} + \sum_{k_2=k_1}^{k-1} p_{ijk_2}^0 + \sum_{l'_1 \in V_1^*} \varepsilon_{l'_1} + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0) \cdot s_{I(ijk)}^0 - \sum_{l'_2 \in V_2^* - \{o_{ijk_1}\}} \varepsilon_{l'_2} \right) \end{aligned} \quad (44)$$

Because $s_{ijk_1} + \sum_{k_2=k_1}^{k-1} p_{ijk_2}^0 + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0) > s_{I(ijk)}^0$ and $e_{I(ijk)}^0 < e_{ijk_1} + \sum_{k_2=k_1+1}^k p_{ijk_2}^0 + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0)$, $s_{ijk_1} + \sum_{k_2=k_1}^{k-1} p_{ijk_2}^0 + \sum_{l'_1 \in V_1^*} \varepsilon_{l'_1} + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0) > s_{I(ijk)}^0 - \sum_{l'_2 \in V_2^* - \{o_{ijk_1}\}} \varepsilon_{l'_2}$ and $e_{I(ijk)}^0 - \sum_{l'_2 \in V_2^*} \varepsilon_{l'_2} < e_{ijk_1} + \sum_{k_2=k_1+1}^k p_{ijk_2}^0 + \sum_{l'_1 \in V_1^* - \{o_{ijk_1}\}} \varepsilon_{l'_1} + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0)$. Then the formula (44) can be rewritten as follows:

$$\begin{aligned} & (\chi_{I(ijk)}^{ijk}) = \left(\min \left(e_{ijk_1} + \sum_{k_2=k_1+1}^k p_{ijk_2}^0 + \sum_{l'_1 \in V_1^* - \{o_{ijk_1}\}} \varepsilon_{l'_1} + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0) \cdot e_{I(ijk)}^0 - \sum_{l'_2 \in V_2^*} \varepsilon_{l'_2} \right) \right. \\ & \quad \left. - \max \left(s_{ijk_1} + \sum_{k_2=k_1}^{k-1} p_{ijk_2}^0 + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0) \cdot s_{I(ijk)}^0 - \sum_{l'_2 \in V_2^* - \{o_{ijk_1}\}} \varepsilon_{l'_2} \right) + \sum_{l'_1 \in V_1^*} \varepsilon_{l'_1} \right) \\ &= \min \left(e_{ijk_1} + \sum_{k_2=k_1+1}^k p_{ijk_2}^0 + \sum_{l'_1 \in V_1^* - \{o_{ijk_1}\}} \varepsilon_{l'_1} + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0) \cdot e_{I(ijk)}^0 \right) \\ & \quad - \max \left(s_{ijk_1} + \sum_{k_2=k_1}^{k-1} p_{ijk_2}^0 + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0) \cdot s_{I(ijk)}^0 - \sum_{l'_2 \in V_2^* - \{o_{ijk_1}\}} \varepsilon_{l'_2} \right) - \sum_{l'_1 \in V_1^*} \varepsilon_{l'_1} - \sum_{l'_2 \in V_2^*} \varepsilon_{l'_2} \\ &= \min \left(e_{ijk_1} + \sum_{k_2=k_1+1}^k p_{ijk_2}^0 + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0) \cdot e_{I(ijk)}^0 \right) \\ & \quad - \max \left(s_{ijk_1} + \sum_{k_2=k_1}^{k-1} p_{ijk_2}^0 + \sum_{k_3=k_1}^{k-1} u(z_{ijk_3}^0, z_{i,j,k_3+1}^0) \cdot s_{I(ijk)}^0 \right) - \sum_{l'_1 \in V_1^*} \varepsilon_{l'_1} - \sum_{l'_2 \in V_2^*} \varepsilon_{l'_2} \\ &= \chi_{I(ijk)}^{ijk} - \sum_{l'_1 \in V_1^*} \varepsilon_{l'_1} - \sum_{l'_2 \in V_2^*} \varepsilon_{l'_2} \end{aligned} \quad (45)$$

If $\sum_{l'_1 \in V_1^*} \varepsilon_{l'_1} + \sum_{l'_2 \in V_2^*} \varepsilon_{l'_2} - \chi_{I(ijk)}^{ijk} \geq 0$, then $(\chi_{I(ijk)}^{ijk})' \leq 0$. It can resolve the

processing conflict between o_{ijk} and $o_{I(ijk)}$ synchronously by adjusting the processing time of operations of L_{ij} and charge L_{ij}^{ij} . So, according to the classification of processing conflict of scheduling plan (section 2.3), the abnormal condition is three-level processing conflict ζ_{23} .

To sum up, if $\varepsilon_{l_1} + \varepsilon_{l_2} - \chi_{I(ijk)}^{ijk} < 0$, then let $\varepsilon_l = 0$ for the nodes $l|l \in V, l \notin V_1, l \notin V_2$. If $\sum_{l'_1 \in V_1^*} \varepsilon_{l'_1} + \sum_{l'_2 \in V_2^*} \varepsilon_{l'_2} - \chi_{I(ijk)}^{ijk} \geq 0$, then the

abnormal condition of scheduling plan is three-level processing conflict ζ_{23} .

(5) If $\sum_{l'_1 \in V_1^*} \varepsilon_{l'_1} + \sum_{l'_2 \in V_2^*} \varepsilon_{l'_2} - \chi_{I(ijk)}^{ijk} < 0$ when $\varepsilon_l = 0$ for the nodes $l|l \in V, l \notin V_1, l \notin V_2$ and $\tilde{\chi}_{I(ijk)}^{ijk} \leq 0$ for the nodes $l|l \in V$, then the abnormal condition of scheduling plan is four-level processing conflict ζ_{24} .

Proof. According to above analysis, it can not resolve the processing conflict between o_{ijk} and $o_{l(ijk)}$ synchronously by adjusting the processing time of operations of L_{ij} and the charge including $o_{l(ijk)}$ if $\sum_{l_1 \in V_1^*} \varepsilon_{l_1} + \sum_{l_2 \in V_2^*} \varepsilon_{l_2} - \tilde{\chi}_{l(ijk)}^{ijk} < 0$. The processing conflict may be resolved synchronously by adjusting the processing time of operations of L_{ij} , the charge including $o_{l(ijk)}$ and other charges. Section 4.3.4 analyzes the new processing conflict time in detail when buffer units are considered and the new processing conflict time $\tilde{\chi}_{l(ijk)}^{ijk}$ is obtained according to the formula (26). Moreover, according to the analysis of formula (26) in section 4.3.4, it can resolve the processing conflict between o_{ijk} and $o_{l(ijk)}$ synchronously by adjusting the processing time of operations of L_{ij} , charge including $o_{l(ijk)}$ and other charges if $\tilde{\chi}_{l(ijk)}^{ijk} \leq 0$ when $\varepsilon_l \neq 0$ for the nodes $l|l \in V$. So, the abnormal condition is four-level processing conflict ζ_{24} according to the classification of processing conflict of scheduling plan (section 2.3).

(6) For the nodes $l|l \in V$, if $\tilde{\chi}_{l(ijk)}^{ijk} > 0$, then the abnormal condition of scheduling plan is five-level processing conflict ζ_{25} .

Proof. According to above analysis, if $\tilde{\chi}_{l(ijk)}^{ijk} > 0$ when $\varepsilon_l \neq 0$ for the nodes $l|l \in V$, it can not resolve the processing conflict between o_{ijk} and $o_{l(ijk)}$ only by adjusting the processing time of operations of L_{ij} , charge including $o_{l(ijk)}$ and other charges. Because $\tilde{\chi}_{l(ijk)}^{ijk} > 0$ for the nodes $l|l \in V$, the original buffer capacity can not satisfy the demand for resolving the processing conflict. The only way is to increase the buffer capacity which can affect the o_{ijk} and $o_{l(ijk)}$. It can change the buffer units which affect the o_{ijk} and $o_{l(ijk)}$ by adjusting the processing machines of operations at steelmaking stage and refining stage. Then it may resolve the processing conflict between o_{ijk} and $o_{l(ijk)}$ by the new buffer units, namely adjusting the processing time of operations at each stage. We can obtain the new processing conflict time (denoted as $(\tilde{\chi}_{l(ijk)}^{ijk})'$) according to the formula (26) when the new buffer units are considered. If $(\tilde{\chi}_{l(ijk)}^{ijk})' \leq 0$, the processing conflict can be resolved by the new buffer units. So, according to the classification of the processing conflict of scheduling plan (section 2.3), the abnormal condition is five-level the processing conflict ζ_{25} .

5. Industrial Application

5.1. Application Background

The Baosteel factory of China can produce 1 000 kinds steel grade. There are three parallel converters of 250 t at steel making stage (4LD, 5LD, 6LD), three kinds of refining machines (5RH-1, 5RH-2, 3RH, LF-1, LF-2, IR_UT) at the refining stage, and three continuous casters (4CC, 5CC, 6CC). The number of refining processing ranging is from 1 to 4, and refining routes are more than 20. The computer systems have the level 2 computer system of process control and the level 3 computer system of region management. In the SMCC production process, operation time delay often occurs which may lead to planned casting break or processing conflict so that the initial scheduling plan becomes unrealizable. The rescheduling for the operation time delay is mainly relies on manual adjustment. The rescheduling methods are simply divided into four categories by the artificial experience: (1) if the operation time delay is within five minutes, then the scheduling plan is not adjusted. (2) If the operation time delay is between five minutes and ten minutes, then adjusting the starting time and the completion time of all operations. (3) If the operation time delay is between ten minutes and thirty minutes, then adjusting the processing machine, the starting time and the completion time of all operations. (4) If the operation time delay is

greater than thirty minutes, then using other methods. Existing manual rescheduling methods with disturbances don't analyze the influence degree of disturbances to the initial scheduling plan in detail, so the adjustment degree of initial scheduling plan is always too greater, which leads to the poor continuity and stability of initial scheduling plan.

5.2. Application Example

This paper takes the actual rescheduling problem in BaoSteel plant for example. **Figure 3** shows the scheduling plan information at time t_1 . The cast one is processed on 4CC and $\Omega_1 = \{L_{11}, L_{12}, L_{13}, L_{14}, L_{15}, L_{16}, L_{17}\}$. The cast two is processed on 5CC and $\Omega_2 = \{L_{21}, L_{22}, L_{23}, L_{24}, L_{25}, L_{26}, L_{27}, L_{28}\}$. The cast three is processed on 6CC and $\Omega_3 = \{L_{31}, L_{32}, L_{33}, L_{34}, L_{35}, L_{36}\}$. The standard processing time and processing time range are as shown in **Table 1**.

The processing time of charge on continuous casting machine is related to following facts: the total weight of the molten steel in charge, the average thickness of the slab, the average width of the odd strand slab and the dual slab of charge and pulling speed of the continuous casting machine. If the charge L_{ij} is the first charge in the cast, then the processing time of the charge L_{ij} on continuous casting machine is calculated as follows:

$$P_{i,j,\theta_{ij}} = \frac{\omega_{ij} \times 10^6}{\alpha_{ij} \times \frac{\zeta_{ij}^1 + \zeta_{ij}^2}{2} \times 7.8 \times 2 \times (v_{ij} - 0.2)} \dots (46)$$

where ω_{ij} is the total weight of the molten steel in charge L_{ij} , α_{ij} is the average thickness of the slab of charge L_{ij} and v_{ij} is the pulling speed. The ζ_{ij}^1 and ζ_{ij}^2 are the average width of the odd strand slab and the dual slab of charge L_{ij} , respectively. If the charge L_{ij} is not the first charge in the cast, then the processing time of the charge L_{ij} on continuous casting machine is calculated as follows:

$$P_{i,j,\theta_{ij}} = \frac{\omega_{ij} \times 10^6 - \gamma_{ij} \times 31.2 \times (\zeta_{ij}^1 + \zeta_{ij}^2 + \zeta_{i,j-1}^1 + \zeta_{i,j-1}^2)}{\alpha_{ij} \times \frac{(\zeta_{ij}^1 + \zeta_{ij}^2 + \zeta_{i,j-1}^1 + \zeta_{i,j-1}^2)}{4} \times 7.8 \times 2 \times (v_{ij} - 0.2)} + \frac{8}{v_{ij} - 0.2} \dots (47)$$

where ω_{ij} is the total weight of the molten steel in charge L_{ij} , α_{ij} is the average thickness of the slab of charge L_{ij} and v_{ij} is the pulling speed. The ζ_{ij}^1 and ζ_{ij}^2 are the average width of the odd strand slab and the dual slab of charge L_{ij} , respectively. The $\zeta_{i,j-1}^1$ and $\zeta_{i,j-1}^2$ are the average width of the odd strand slab and the dual slab of charge $L_{i,j-1}$, respectively. The pulling speed includes the minimum pulling speed, standard pulling speed, the maximum pulling speed. The processing time of charges on continuous casting machine is shown in **Tables 2** and **3** according to the formula (46) and formula (47). The transportation time is as shown in **Table 4**.

The scheduling plan at time t_2 ($t_2 = 14:21$) is shown in **Fig. 4**. The operation o_{241} on 5LD is starting at time 14:21, that is $s_{241}^* = 14:21$. The abnormal condition prediction of the scheduling plan is made as follows according to the pro-

Table 1. The processing time of operations at steelmaking and refining stage.

Machine	LD		RH		LF		IR_UT	
	Standard	Interval	Standard	Interval	Standard	Interval	Standard	Interval
Processing time (m)	35	[32,38]	20	[15,30]	30	[22,35]	30	[25,35]

posed method:

(1) Get event information: $m = 2LD$, $o = o_{241}$, $\chi = 1$. $\tau = s_{241}^* - s_{241}^0 = 20 > 0$ because $s_{241}^0 = 14:01$ and $s_{241}^* = 14:21$, so $y = y_1$, and $Y = \{o_{241}, 2LD, y_1, 20\}$.

(2) The processing time of operations which are being processed or have been processed can not be changed. So, the operations not be processed are only considered when the reachability matrix is established. The correspondence relationship between nodes and operations is shows in Table 5. The κ denotes the idle state, and the μ indicates the interval state between adjacent operations of the same charge.

Table 2. The processing time of charges at casting stage.

Operations	o_{113}	o_{123}	o_{133}	o_{143}	o_{153}	o_{163}	o_{173}	o_{213}	o_{223}	o_{233}	o_{243}
Minimal processing time (m)	45	45	45	50	55	45	40	45	45	50	45
Standard processing time (m)	48	48	49	58	60	46	42	46	46	50	50
Maximum processing time (m)	60	60	61	70	75	60	60	60	60	65	65

Table 3. The processing time of charges at casting stage.

Operations	o_{253}	o_{263}	o_{273}	o_{283}	o_{313}	o_{323}	o_{333}	o_{343}	o_{353}	o_{363}
Minimal processing time (m)	45	50	45	45	60	60	60	60	60	60
Standard processing time (m)	50	55	52	54	74	74	76	76	76	77
Maximum processing time (m)	65	70	67	70	85	85	85	85	85	85

Table 4. The transportation time between machines.

Transportation time	4LD	5LD	6LD	5RH-1	5RH-2	3RH	LF-1	LF-2	IR_UT	4CC	5CC	6CC
4LD	0	12	13	10	10	13	15	15	13	16	15	14
5LD		0	12	15	15	13	15	15	13	16	15	14
6LD			0	15	15	13	15	15	13	16	16	15
5RH-1				0	18	21	20	18	23	22	25	25
5RH-2					0	21	20	18	23	22	25	25
3RH						0	20	21	18	25	22	22
LF-1							0	18	21	22	25	25
LF-2								0	23	22	25	25
IR_UT									0	25	22	22
4CC										0	16	16
5CC											0	13
6CC												0

Table 5. The correspondence relationship between nodes and operations.

Node	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Operation	o_{151}	κ_{161}^{151}	o_{161}	κ_{171}^{161}	o_{171}	o_{241}	κ_{251}^{241}	o_{251}	κ_{261}^{251}	o_{261}	κ_{271}^{261}	o_{271}	κ_{281}^{271}	o_{281}	o_{331}	κ_{341}^{331}	o_{341}	κ_{351}^{341}	o_{351}	κ_{361}^{351}
Node	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
Operation	o_{361}	μ_{152}^{151}	μ_{162}^{161}	μ_{172}^{171}	μ_{242}^{241}	μ_{252}^{251}	μ_{262}^{261}	μ_{272}^{271}	μ_{282}^{281}	μ_{332}^{331}	μ_{342}^{341}	μ_{352}^{351}	μ_{362}^{361}	o_{142}	κ_{152}^{142}	o_{152}	κ_{162}^{152}	o_{162}	κ_{172}^{162}	o_{172}
Node	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60
Operation	o_{242}	κ_{252}^{242}	o_{252}	κ_{262}^{252}	o_{262}	κ_{272}^{262}	o_{272}	κ_{282}^{272}	o_{282}	o_{332}	κ_{342}^{332}	o_{342}	κ_{352}^{342}	o_{352}	κ_{362}^{352}	o_{362}	μ_{143}^{142}	μ_{153}^{152}	μ_{163}^{162}	μ_{173}^{172}
Node	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80
Operation	μ_{243}^{242}	μ_{253}^{252}	μ_{263}^{262}	μ_{273}^{272}	μ_{283}^{282}	μ_{333}^{332}	μ_{343}^{342}	μ_{353}^{352}	μ_{363}^{362}	o_{133}	o_{143}	o_{153}	o_{163}	o_{173}	o_{233}	o_{243}	o_{253}	o_{263}	o_{273}	o_{283}
Node	81	82	83	84	85															
Operation	o_{323}	o_{333}	o_{343}	o_{353}	o_{363}															

(3) It can be known that the o_{241} is the corresponding operation for the node 6 according to the Table 5. The planned casting break time $\gamma_{3,4}^2$ between charge L_{23} and charge L_{24} is calculated as follows according to the formula (18): $\gamma_{3,4}^2 = e_{241}^0 + \Delta t + p_{242}^0 + u(z_{241}^0, z_{242}^0) + u(z_{242}^0, z_{2423}^0) - e_{233}^0 = 20$. Because $\gamma_{3,4}^2 > 0$, the planned casting break between L_{23} and L_{24} occurs. Because $p_{233}^{\max} - p_{233}^0 - \gamma_{3,4}^2 = 65 - 20 - 20 = -5 < 0$, let $\varepsilon_l = 0 | l \notin V_{24}$, then the planned casting break time $\tilde{\gamma}_{3,4}^2$ between L_{23} and L_{24} is calculated as follows according to the formula (27): $\tilde{\gamma}_{3,4}^2 = \eta_{76} - \lambda_{75} = 12 > 0$ and $p_{233}^{\max} - p_{233}^0 - \tilde{\gamma}_{3,4}^2 = 3 > 0$, so the abnormal condition of planned casting break is two-level planned casting break ζ_{12} .

(4) The processing conflict time χ_{251}^{241} of charge L_{24} on 5LD is calculated as follows according to the formula (15): $\chi_{251}^{241} = \min(e_{241}^0 + \Delta t, e_{251}^0) - \max(s_{241}^0 + \Delta t, s_{251}^0) = 5 > 0$, so

Fig. 3. The scheduling plan at time t_1 .

Fig. 4. The scheduling plan at time t_2 .

the processing conflict between L_{24} and L_{25} on 5LD occurs. Because $\varepsilon_6 - \chi_{251}^{241} = -2 < 0$, $\varepsilon_8 - \chi_{251}^{241} = -2 < 0$ and $\varepsilon_6 + \varepsilon_8 - \chi_{251}^{241} = 1 > 0$, then the abnormal condition of processing conflict is two-level processing conflict ζ_{22} .

(5) The processing conflict time χ_{252}^{242} is calculated as follows according to the formula (15): $\chi_{252}^{242} = \min(e_{241}^0 + \Delta t + u(z_{241}^0, z_{242}^0) + p_{242}^0, e_{252}^0) - \max(e_{241}^0 + \Delta t + u(z_{241}^0, z_{242}^0), s_{252}^0) = -10 < 0$, so there is no processing conflict between L_{24} and L_{25} on 5RH-2.

(6) The processing conflict time χ_{253}^{243} is calculated as follows according to the formula (15): $\chi_{253}^{243} = \min(e_{241}^0 + \Delta t + u(z_{241}^0, z_{242}^0) + p_{242}^0 + u(z_{242}^0, z_{243}^0) + p_{243}^0, e_{253}^0) - \max(e_{241}^0 + \Delta t + u(z_{241}^0, z_{242}^0) + p_{242}^0 + u(z_{242}^0, z_{243}^0), s_{253}^0) = 20 > 0$, so the processing conflict between L_{24} and L_{25} on 5CC occurs. $\varepsilon_{76} - \chi_{253}^{243} = -15 < 0$, $\varepsilon_{77} - \chi_{253}^{243} = -15 < 0$ and $\varepsilon_{76} + \varepsilon_{77} - \chi_{253}^{243} = -10 < 0$. When let $\varepsilon_l = 0 | l \notin V_{24}, l \notin V_{25}$, $\tilde{\chi}_{253}^{243} = -1 < 0$, so the abnormal condition of processing conflict is three-level processing conflict ζ_{23} .

5.3. Application Effect

According to the above application example, it can be known that abnormal condition of scheduling plan with operation time delay disturbance are determined according to the proposed method when the operation delay time of o_{241} is twenty minutes. (1) The abnormal condition of planned casting break between the charge L_{23} and the charge L_{24} on 5CC is two-level planned casting break ζ_{12} , so the planned casting break between charge can be resolved synchronously by adjusting the processing time of L_{23} at continuous casting stage and the processing time of L_{24} at each stage. (2) The abnormal condition of processing conflict between the charge L_{24} and the charge L_{25} on 5LD is two-level processing conflict ζ_{22} , so the processing conflict between charge L_{24} and L_{25} can be resolved synchronously by adjusting the processing time of L_{24} and L_{25} on 5LD. (3) The abnormal condition of processing conflict between the charge L_{24} and the charge L_{25} on 5CC is three-level processing conflict ζ_{23} , so the processing conflict between charge L_{24} and L_{25} can be resolved synchronously by adjusting the processing time of L_{24} and L_{25} on each stage. Because the operation delay time of o_{241} is twenty minutes which is between ten minutes and thirty minutes, the abnormal condition of the scheduling plan will be resolved by adjusting the processing machine, the starting time and the completion time of all operations according to the manual method. The proposed method can solve the abnormal condition only by adjusting the processing time of some charges, which can maintain the good continuity and stability.

6. Conclusions

In the steelmaking and continuous casting (SMCC) production process, operation time delay often occurs which

may lead to planned casting break or processing conflict so that the initial scheduling plan becomes unrealizable. Existing rescheduling methods don't analyze the influence degree of disturbances to the initial scheduling plan in detail, so the adjustment degree of initial scheduling plan is always too greater, which leads to the poor continuity and stability of initial scheduling plan. In this paper, the relation among operation time delay, planned casting break and processing conflict is firstly deeply analyzed. Then a novel prediction method for abnormal condition of scheduling plan with operation time delay disturbance in SMCC production process is proposed including disturbance identification of operating time delay based on event-driven mechanism, analysis on charges based on reachability matrix, analysis on influence degree of disturbance and abnormal condition decision of initial scheduling plan. The real-time application shows that the proposed prediction method can timely and accurately predict the abnormal condition of the scheduling plan with operation time delay disturbance, which can only adjust the affected charges that must to be rescheduled in the initial scheduling plan and reduce the frequency of complete rescheduling. The initial scheduling plan can also maintain the good continuity and stability.

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