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Scheduling Optimization of Printed Circuit Board Micro-Hole Drilling Production Line Based on Complex Events

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Abstract: The interdependence between the scheduling method and the production efficiency of a micro-hole drilling production line for printed circuit boards (PCBs) holds significant importance, necessitating the optimization of such a production line's scheduling. Consequently, this research paper presents a scheduling optimization approach for the micro-hole drilling production line of a PCB, utilizing complex events as its foundation. Initially, a complex event model was constructed to establish correlations among extensive production line data. Subsequently, the typical complex events associated with the micro-hole drilling production line of a PCB were defined, thereby enabling the all-around monitoring of the operation state of such a production line. Furthermore, this study presents the establishment of a production scheduling model for PCB micro-hole drilling. With the goal of minimizing the maximum completion time, the catastrophe genetic algorithm was used to solve the initial scheduling scheme of the printed circuit board micro-hole drilling production line. The reliability and effectiveness of the catastrophe genetic algorithm in solving the hybrid-driven production scheduling problem of complex events were verified. Dynamic scheduling was performed when three complex events occurred in the production line: emergency order insertion, abnormal equipment operation, and tool failure. The scheduling optimization rate after identifying the emergency insertion event could reach 25.1%. The scheduling optimization rate of the production equipment operation event was related to the specific failure time of the equipment. The scheduling optimization rate after identifying the tool failure event could reach 25%. Rescheduling immediately after identifying the tool failure event could exert no effect on the initial scheduling process. It was proven that the identification and rescheduling of complex events can improve the production efficiency of a PCB micro-hole drilling production line.

Keywords: micro-hole drilling; production line; complex event; emergency insertion; tool failure

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1. Introduction

As key components of communication systems, printed circuit boards (PCBs) support the rapid development of the new generation of information and communication technologies, such as the Internet of Things, big data, and artificial intelligence [1]. Micro-drilling production on a PCB is the basic requirement for the information interconnection of communication products [2]. How to improve the fluency and intelligence level of a PCB micro-drilling production line is one of the key challenges faced by PCB manufacturing enterprises [3]. Production scheduling is a decision-making process concerning the production line. As the nerve center of production process control, it allocates resources to tasks in a specific order within a given time [4]. Because the amount of data generated in the manufacturing process is too large and complex, it is difficult to perceive, transmit, and process, which easily leads to untimely decision-making, thereby reducing production efficiency and increasing resource losses [5]. Therefore, it is of great significance to optimize the production scheduling of PCB micro-hole drilling production lines.

At present, the optimization of production scheduling mainly focuses on two aspects: massive data processing and the optimization algorithm [6]. In terms of data processing, since the sensing of real-time data in a production line is completed via a large number of sensor nodes, there is a large number of redundant and invalid data in the sensing process [7]. However, due to the lack of effective automatic identification and acquisition system solutions for this real-time, multi-source information, there are phenomena such as time-consuming collection without added value, serious lag, and error-proneness when acquiring multi-source information [8]. Complex event processing technology can quickly process large amounts of data from various sources according to the consistency of the data, thereby generating accurate results to guide the production process [7]. In order to monitor an abnormal situation in the workplace, Lu et al. [9] used complex event-processing technology to correlate context information, accurately extracted data to monitor abnormal situations, and then established an abnormal complex event model. Li Zhe et al. [10] combined the complex event model and RFID technology to realize the comprehensive monitoring of a production line via monitoring the abnormal data in the production process in real time. In order to improve the scheduling ability of the production line with higher precision and faster efficiency, Ding et al. [11] proposed an analysis method using RFID-generated data based on complex-event-driven information, which realized the accurate processing of massive data. Wang et al. [12] associated RFID data with event information to form an original event and standardized the RFID event model, combined it with a detection engine, and more effectively and quickly dealt with complex events composed of RFID data. In addition, Mehdiyev N et al. [13] established a model to predict business processes and standardize control, and they proposed a standardized process control framework based on complex-event-driven information, which laid a theoretical foundation for achieving accurate production scheduling. Govindasamy et al. [14] proposed a probabilistic, complex event processing method based on an RFID automobile manufacturing environment, which uses complex event processing technology to process continuous flow probability data and uncertain data, effectively reduces the processing time and throughput of the system, and optimizes the scheduling ability of the production line. The production process of PCB micro-hole drilling is relatively complex, the machining process is obvious in stages, the process is discrete, and there are abnormal events, such as emergency insertion, abnormal equipment operation, and tool fracture failure [15]. The arrival of emergency orders in the production process will affect the existing scheduling scheme and even cause the order to delay delivery [16,17]; the abnormal operation of equipment in production will interrupt the production process and reduce production efficiency [18]; in the process of micro-hole drilling, tool fracture failure can easily lead to the scrapping of the sheet, reducing production efficiency and wasting too much resources [19,20]. Therefore, it is very important to find and identify the emergency insertion orders, abnormal equipment operation, and tool fracture failure in the PCB micro-hole drilling production process in time so as to rearrange production scheduling. According to the above review, it can be seen that complex event processing technology can quickly analyze and locate requirements from a continuous event flow, accurately identify abnormal conditions in the production process, and apply them to a PCB micro-hole drilling production line to optimize production scheduling when abnormal conditions occur in a timely and effective manner.

In terms of algorithms, heuristic algorithms are widely used to solve production scheduling problems [21], and they have achieved remarkable results. Common algorithms include the discrete whale algorithm, migratory bird optimization algorithm, reinforcement learning algorithm, and genetic algorithm. In order to solve the single-objective, flexible job shop scheduling problem with a minimum makespan, Caldeira et al. [22] proposed an improved Jaya algorithm that can efficiently balance the exploration and utilization of the search space. Yan Xu et al. [23] proposed the quantum whale optimization algorithm, which improves the shortcomings of the traditional whale optimization algorithm in solving flexible job shop scheduling. Jiang et al. [24] proposed the discrete grey wolf optimization algorithm, which can maintain the diversity in the population and solve the problem of the premature convergence of the grey wolf optimization algorithm. In order to solve HFSP, HAN et al. [25] improved the migratory bird optimization algorithm, and they adopted new acceptance criteria and competition mechanisms to ensure the diversity of the population and the exploration ability of the algorithm. Zhang Jie et al. [26] used the wolf algorithm in FJSP for the first time, and they completed the process of solving the job shop scheduling problem based on the wolf algorithm. However, the scope of application of the above algorithm based on the characteristics of animal behavior in nature will be limited, it is not applicable to all problems, ref. [27] and the reinforcement learning algorithm requires a lot of training data and time. For complex job shop scheduling problems, it takes a longer training time to get better results [28]. The genetic algorithm is more suitable for the optimization of complex problems because of its characteristics of the independence of the problem model, global optimality, random transfer, rather than certainty, implicit parallelism, etc. [29]. It is the best choice to solve the scheduling problem of a PCB micro-hole drilling production line. Liu et al. [30] improved the framework of the traditional genetic algorithm and effectively improved the convergence and accuracy of the traditional genetic algorithm. In order to make up for the deficiency of the genetic algorithm, Wu Shujing et al. [31] designed a mechanism to preserve excellent individuals and improve the search ability of the genetic algorithm. Zhou et al. [32] proposed an ant colony algorithm with the goal of minimizing the maximum completion time for the two problems of prematurity and instability in the genetic algorithm to solve the job shop scheduling problem. The catastrophe operator can randomly select some genes from the individual genes to mutate, thereby generating new individuals. This can increase the diversity of the population and help to avoid the algorithm's falling into the local optimal solution. In addition, the catastrophe operator can also increase the global search ability of the algorithm, thereby improving the convergence speed and convergence accuracy of the algorithm. By introducing the catastrophe operator, the algorithm can search the solution space more comprehensively so as to find a better solution.

This paper firstly uses complex event processing technology to correlate complex events with production data, forming complex events represented by emergency order insertion events and production line equipment operation events. At the same time, the real-time data of the tool and the remaining useful life model are correlated to form the tool failure event so as to establish the complex event model of the production line. Then, the production scheduling model based on the experimental platform of a PCB micro-hole drilling production line is established, and the solution process of the traditional genetic algorithm is processed to solve the initial scheduling scheme. Then, the emergency insertion order, production line equipment operation, and prediction of the tool's remaining useful life are taken as abnormal events, and a complex-event-driven production scheduling model is formed. Finally, the reliability and effectiveness of the catastrophe genetic algorithm in solving the complex-event–hybrid-driven production scheduling problem are verified using an example simulation. It is proven that the identification and rescheduling of complex events are very important to improve the production efficiency of a PCB micro-hole drilling production line.

2. Establishment of a Complex Event Model

In the process of processing massive production data, the related concepts and definitions of events are different. This paper abstracts the definitions of various literatures and sets the following definitions:

Original event: This refers to the original data collected during the production process, which is simple and repetitive. The data are fragmented, and there is a large number of label data, also known as label events;

Complex event: This refers to the combination of original events according to certain logical rules to generate events with higher levels of guiding significance, also known as complex events.

In the production process of a PCB micro-hole drilling production line, there are many processes, such as outbounds, AGV transfer, marking, PCB drilling, detection, and so on. The equipment includes an intelligent warehouse, an AGV trolley, a transfer robot, a conveyor belt, a marking machine, a drilling machine, and detection equipment. The processing of a PCB will produce a lot of RFID data stream and equipment running state data. Through complex event processing, these data can be processed in real time. In this study, complex event processing was carried out according to the data of processing equipment and sensing equipment. The representative complex events are summarized as follows: an emergency order insertion event based on RFID data, a production line equipment operation event based on equipment operation data, and a tool failure event. They provide a massive source of complex events for the production scheduling of a PCB micro-hole drilling production line.

2.1. Production Equipment Operation Event

In order to better perceive the running state of the equipment, in this study, we collected the operation state data of the equipment for the experimental platform of a PCB micro-hole drilling production line and processed the complex events on their basis.

For the detection equipment running state event, we described the event for which the visual inspection equipment detected the specified object, which included information such as the type of item, test results, and test time. Part of the encapsulation code is shown in Box 1.

Box 1. Equipment operation event encapsulation code.

```
<CEvent name="VisionDetection" type="complex">
<eid value="event6"/>
<timestamp value="2023-03-17T19:00:00Z"/>
<equipmentId value="TEST-01"/>
<equipmentStatus value="active"/>
<testType value="pressure"/>
<testValue value="10.5"/>
<testUnit value="kPa"/>
<error value="none"/>
</PEvent>
```

2.2. Emergency Insertion Event

Through the complex event processing system, the data stream can be processed in real time to form various complex RFID events in the production process. Through the analysis and processing of complex events, dynamic production scheduling can be realized using emergency insertion events.

The emergency order insertion event (IEC) refers to the insertion of a higher-priority work plan in the original production plan due to the system's scheduling during the PCB production process, resulting in an overall processing quantity greater than the original planned processing quantity because, after the arrival event (type = 'RFID_arrival'), the RFID departure event (type = 'RFID_departure') will occur. And both events occur on a workstation (location = 'workstation'). Then, if multiple such events occur continuously over a period of time (here, set to 10 s), and the total number exceeds the planned number of processing, then an emergency order insertion event can be considered to have occurred. The state monitoring sentences of EPL are shown in Box 2.

Box 2. Monitoring sentences of EPL.

```
SELECT count(*) as cnt
FROM RFIDEvent(type='RFID_departure', location='workstation').win:time(10 sec) as e1,
RFIDEvent(type='RFID_arrival', location='workstation', AID=e1.AID).win:time(10 sec) as e2
HAVING count(*) > original_plan_num
```

2.3. Tool Failure Event

In the actual production process of a PCB micro-hole drilling production line, the status and monitoring of the production line can be reflected in real time by effectively using the data collected in real time. At the same time, through the processing of a large number of historical data, the mechanism model of the tool and equipment can be constructed. These models can be combined with real-time data to achieve the active prediction of the production process. The main research content of this section was to construct a tool with a remaining useful life prediction model based on historical data and combine the model with real-time collected data to form a complex event of the tool's remaining useful life prediction. In order to collect a large amount of historical data, in this study, we first built a force measurement platform. In this study, the high-precision micro-force measurement system produced by Kistler Company was selected for data acquisition. The system is composed of a dynamometer, a charge amplifier, a data acquisition card, the computer-side force measurement software DynoWare (2825A-02–2), and other parts.

Figure 1 is the tool's remaining useful life prediction model system. The role of the force measurement platform is to collect real-time data and save historical data. The real-time data are denoised, extracted, and selected via noise reduction, feature extraction, and selection and then input into the tool's remaining useful life prediction based on the similarity principle. The improved model predicts the remaining useful life of the tool, forms a complex event for predicting the remaining useful life of the tool, and finally realizes active prediction dynamic scheduling.

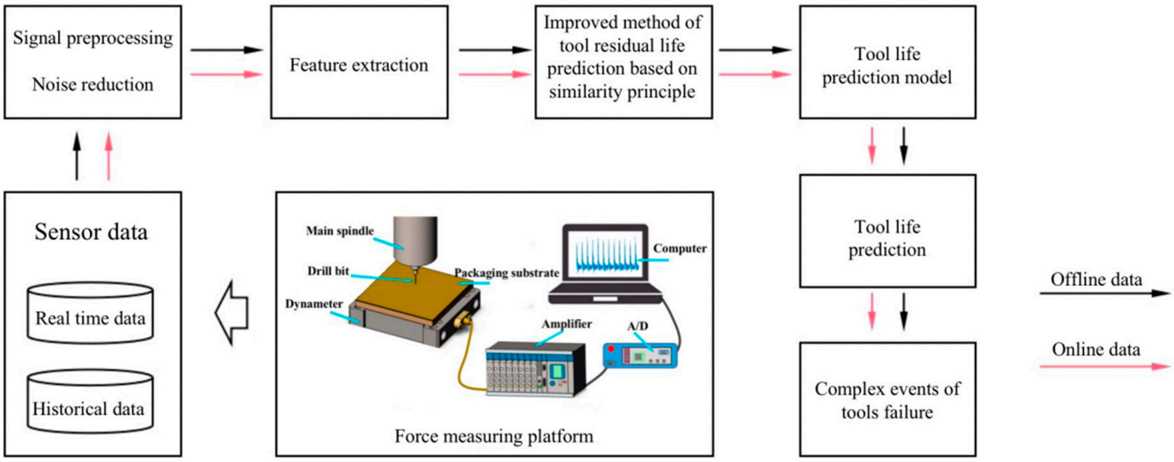

Figure 1. Tool's remaining useful life prediction model system.

Tool failure events were determined as follows:

$$CE_{\text{Tool life prediction}} = e_b(DM_{id}, DT_{id}, RUL, e) \quad (1)$$

where DM_{id} is the drilling equipment ID, DT_{id} is the tool ID, RUL_{id} is the tool's remaining useful life, and e is the sub-events of tool failure.

The remaining useful life of the tool can be predicted using the complex event of the tool's remaining useful life model. The event mainly includes the number of the tool, the remaining useful life of the tool, the measured axial force value and time, and the predicted time. When the remaining service life of the tool is predicted to be lower than a certain threshold, the remaining service life state of the tool becomes 1, indicating that it needs to be replaced actively. Part of the encapsulation code is shown in Box 3.

Box 3. Tool failure event encapsulation code.

```
<CEvent name="Tool life prediction" type="complex">
<eid value="Tool1"/> <!-- the number of tools -->
<operator name="Tool life status" status="1"/> <!-- The remaining service life state of the tool, 1
indicates the need for replacement -->
<operand>
<PEvent name="Axial force measurement" type="primitive">
<eid value="Machine1"/> <!-- the number of drilling machine -->
<force value="150"/> <!-- value of thrust force -->
<time value="2023-03-20T10:30:00"/> <!-- measuring time -->
</PEvent>
</operand>
<time value="2023-03-20T10:31:00"/> <!-- measuring time -->
</CEvent>
```

The tool's remaining useful life prediction model system and real-time sensor data are integrated, that is, the tool's improved remaining useful life prediction model based on the similarity principle can be realized to actively predict the remaining useful life of the tool. Assuming that the current RULb = eb (2, PCB002,267,0) is monitored in real time, the event indicates that the remaining useful life of the drill bit with an ID of PCB002 on the drilling machine is expected to be broken by 267 drilling holes. In order to facilitate the continuous processing timing of PCB micro-hole drilling using the experimental platform and RUL to participate in dynamic processing operation scheduling, RUL is expressed by time. According to the PCB002 drill bit, the drilling time is 3S, and the processing time is 800S. Therefore, according to the actual processing situation, the monitoring event of the processing state of the above RULb = eb (2, PCB002,267,0) drill bit can be expressed as RULb = eb (2, PCB002,800,0), which can be used to provide conditional input for subsequent dynamic production scheduling.

3. Production Scheduling Optimization Based on the Catastrophe Genetic Algorithm

3.1. Establishment of a Scheduling Model

The scheduling problem of a PCB micro-hole drilling production line can be described as an $n \times m$ scheduling problem; that is, the PCB micro-hole-drilling production line has n workpieces to be processed (denoted as workpiece set $J = \{ J_1, J_2, \ldots, J_n\}$), and it can perform different processing on m different equipment (denoted as equipment set $M = \{ M_1, M_2, \ldots, M_m\}$). Each workpiece J_i contains n_i processes (denoted as process set $O_{ij} = \{ O_{i1}, O_{i2}, \ldots, O_{ini}\}$). Each process can choose to be processed on the candidate equipment set M (O_{ij}) (M (O_{ij}) $\subseteq$ M) with processing capabilities. The processing indicator O_{ijk} indicates that the jth process of the workpiece i is processed on the machine k, and the value is 1 or 0, indicating whether it is processed on it or not, $i \in [1, n]$, $j \in [1, m]$, and $k \in [1, m]$. The processing time of the jth process of the workpiece i to be processed on machine k is T_{ijk}, and the starting time of the jth process of the workpiece i to be processed on machine k is S_{ijk}. Then, the completion time of the jth process of job i on machine k is $C_{ijk} = T_{ijk} + S_{ijk}$, and the maximum completion time of job i is $C_{imax} = \Sigma C_{ijk}$.

Production line scheduling constraints:

1. The same workpiece can only be processed by the same equipment once;
2. The processing sequence is fixed;
3. The equipment can only complete a single processing task per unit time;
4. In the initial scheduling, the processing tasks have no priority order;
5. Once processed, the current task must be completed before processing other workpieces;
6. The processing time is greater than zero;
7. The processing time is fixed.

For enterprise managers, the processing time, production cost, and energy consumption of equipment are all problems that need to be considered in production scheduling optimization. How to shorten the processing time, reduce the production cost, reduce the machine load, and improve equipment utilization as much as possible are all problems that need to be considered to improve enterprise efficiency. This paper establishes a scheduling problem of a PCB micro-hole drilling production line with the goal of minimizing total completion time.

Objective function:

$$f_1 = \min(C_{\max}) \tag{2}$$

Optimization rate:

$$f_2 = \frac{C_{\max} - f_1}{C_{\max}} \times 100\% \tag{3}$$

Constraint condition:

$$S_{jk} - (S_{ik} + T_{jk}) + L \times (1 - X_{ijk}) \geq 0 \tag{4}$$

$$S_{ik} - (S_{jk} + T_{jk}) + L \times X_{ijk} \geq 0 \tag{5}$$

$$\sum^{m} O_{ijk} = 1 \tag{6}$$

$$S_{i(j+1)} - C_{ijk} \geq 0 \tag{7}$$

Among them, the goal of Equation (2) is to minimize the maximum completion time. Equation (3) represents the processing time optimization rate of rescheduling immediately after identifying critical events. Equations (4) and (5) show that a machine can only process one job at a time. Equation (6) indicates that each process can only be carried out on one machine. Equation (7) indicates that the next process of the same workpiece must wait for the completion of the previous process.

Firstly, the operator catastrophe processing is carried out for the traditional genetic algorithm. With the goal of minimizing the maximum completion processing time, the initial scheduling scheme and dynamic scheduling scheme are solved for the emergency insertion event, the production line equipment operation event, and the tool failure event as abnormal events. Finally, the feasibility of the production scheduling model based on a data-model–complex-event hybrid drive is verified.

3.2. Catastrophe Genetic Optimization Algorithm

The genetic algorithm is a population search algorithm. Its group search has large coverage, which makes the genetic algorithm face a small risk of falling into the local optimal solution, which is more conducive to global optimization, and the genetic algorithm programming is simpler. The genetic algorithm can select the best individual of the population through fitness function science, and the fitness function does not need to meet the continuous or derivative criteria, so it is easy to build the fitness function and algorithm framework of the research problem. The genetic algorithm achieves strong optimization performance. There is a lot of interference information in the process of seeking the optimal solution in the initial population, which will affect the efficiency and accuracy of the algorithm. The genetic algorithm eliminates invalid interference information through gene selection, recombination, crossover, mutation, and other processes to ensure its high efficiency and high quality. The genetic algorithm achieves strong robustness under different problems. Flow chart as shown in the Figure 2.

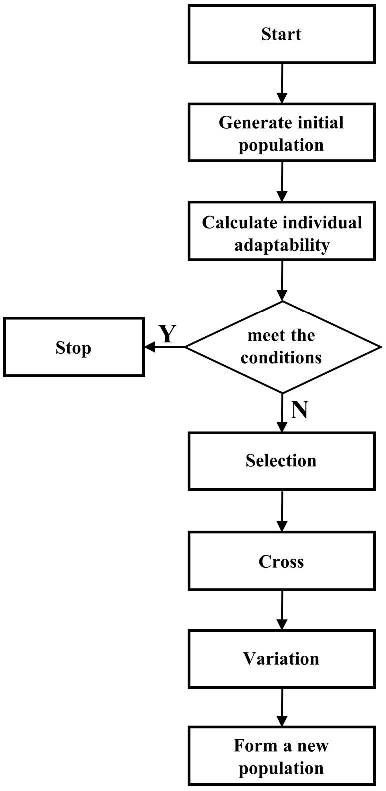

Figure 2. Flow chart of the genetic algorithm.

4. Complex-Event-Driven Dynamic Scheduling Mechanism

As the core equipment of network transmission, PCB is widely used in the communication industry. It is a typical discrete manufacturing and processing product. It includes a wide variety of products and complex forms. Its production has the characteristics of standardization and a large batch. The production process is relatively complex, the processing process is obvious, and the process is discrete. Therefore, the selection of PCB as the processing object to design the physical production line can meet the needs of this paper for flexible manufacturing research. Therefore, it is divided into a physical equipment layer, a data perception layer, a data processing layer, and an application service layer to design the overall architecture of the PCB micro-hole drilling production line experimental platform, as shown in Figure 3.

Events such as emergency order insertion events, production line equipment operation events, and tool failure events directly affect the production of PCBs, resulting in dynamic changes to production scheduling schemes. Complex-event-driven dynamic job scheduling is based on the catastrophe genetic algorithm as the core algorithm to solve the dynamic change in a production line job scheduling scheme caused by a complex event anomaly.

The dynamic scheduling driver mechanism used in this paper is shown in Figure 4. Firstly, it judges whether there are complex events in the PCB drilling production line. If there are complex events, the complex events are judged to determine whether it is a common complex event or a typical complex event on the PCB drilling production line. If it is a common complex event, it will determine whether the event affects the time of the next process according to the minimum processing time as the objective function. If the time exceeds the threshold set by the experimental platform, it will be dynamically adjusted. If the time is short, it will be periodically adjusted. If it is a typical complex event of a PCB drilling production line, it is necessary to judge the type of specific complex event. For abnormal equipment events, it is necessary to judge the processing delay caused by equipment abnormalities. If the delay accounts for less than 10% of the total processing time, one must wait for the equipment to restart. If it is greater than 10%, a new dynamic scheduling scheme is immediately formed via dynamic scheduling. For the emergency insertion event, it is necessary to form a new scheduling scheme after judging the priority of the job type of the insertion order; for the tool failure event, after the system pushes the predicted remaining useful life of the tool, it is necessary to select the appropriate tool change time. In this case, there is no need to reschedule.

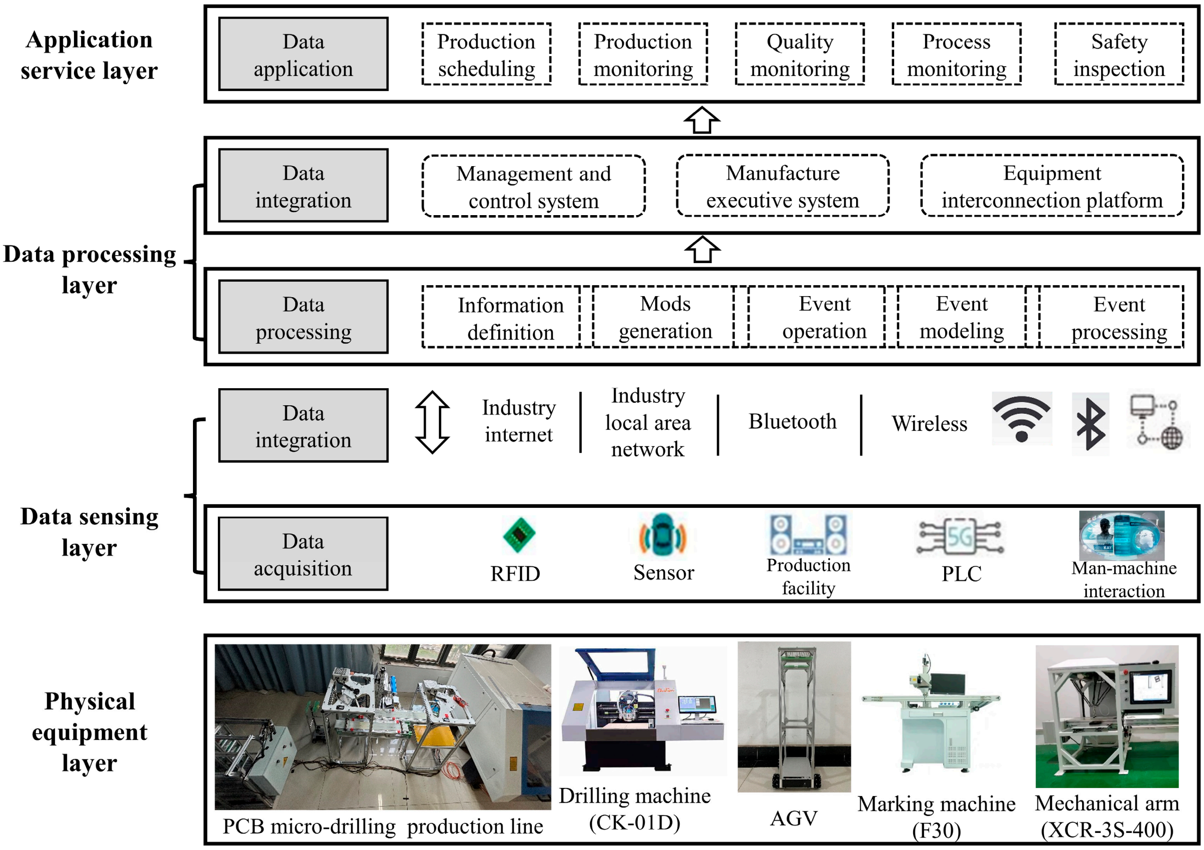

Figure 3. Overall architecture of the intelligent perception platform.

4.1. *Processing Job Scheduling without Disturbance Events*

For the production line without any disturbance event, the traditional genetic algorithm and the catastrophe genetic algorithm were used to solve the scheduling problem and compared. Specifically, according to the built PCB processing production line as the experimental object, for this paper, we set up six different processing workpieces and used five kinds of machine equipment in the production from process to process. The specific data are shown in Table 1. In the order of the first action process, each processing part was processed according to the fixed five processes. The corresponding column under each process indicates that a certain process of the workpiece is processed on machine tool equipment, and the time corresponding to the right side is the time required for the process to complete the processing on the equipment. This paper uses workpiece one (1, 92, 2, 147, 3, 210, 4, 126, 5, 240) as an example for illustration. This means that the workpiece PCB No. 1 board process 1 is processed at equipment 1, the processing time is 92 s, process 2 is processed at equipment 2, the processing time is 147 s, process 3 is processed at equipment 3, the processing time is 210 s, process 4 is processed at equipment 4, the processing time is 126 s, process 5 is processed at equipment 5, and the processing time is 240 s.

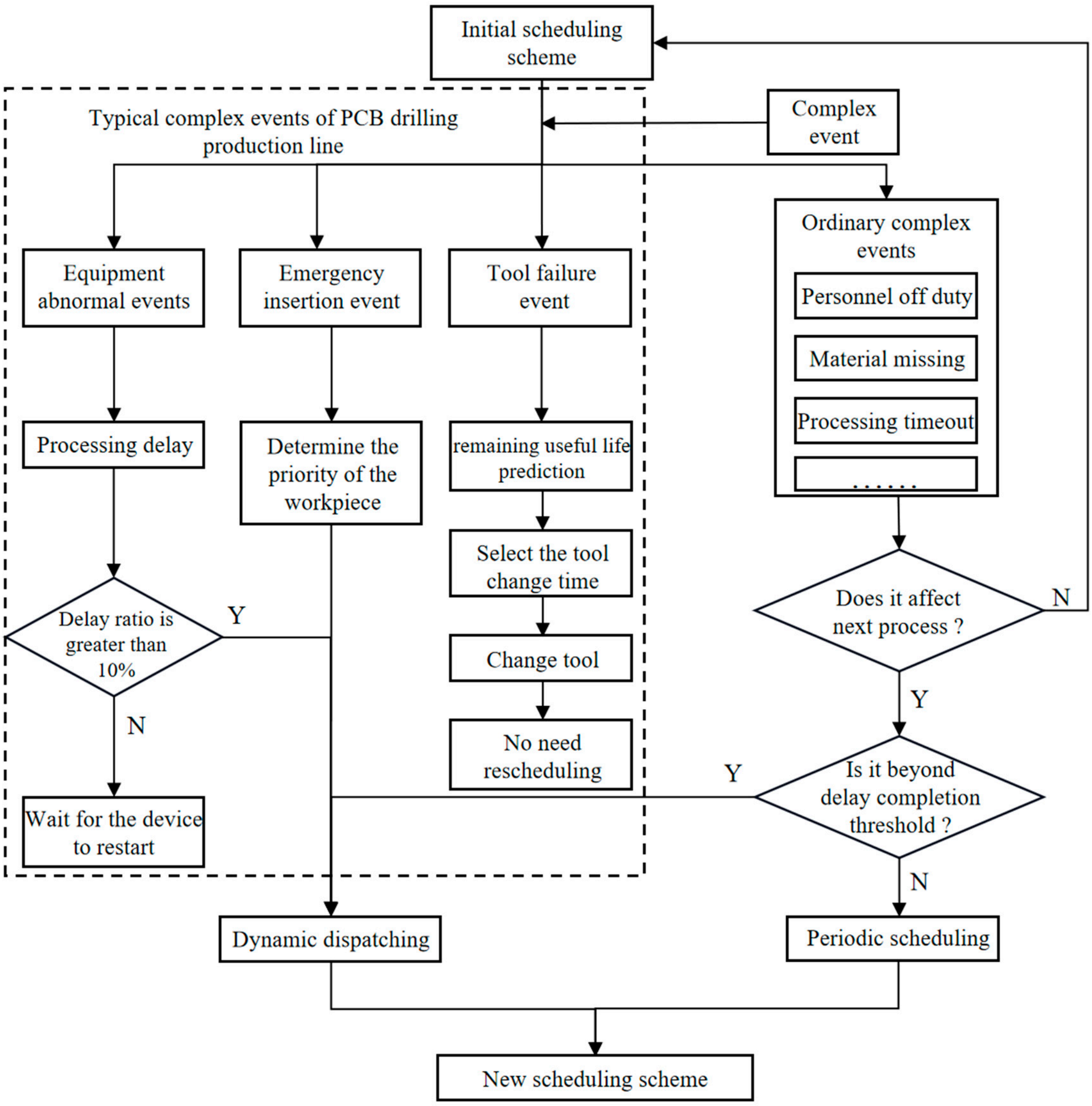

Figure 4. Scheduling flow chart.

Table 1. Process table.

Workpiece	Process 1	Time(s)	Process 2	Time(s)	Process 3	Time(s)	Process 4	Time(s)
1	1	210	2	294	3	420	4	252
2	2	420	3	210	4	336	1	210
3	3	294	1	462	2	336	4	378
4	4	420	3	252	1	210	2	294
5	1	252	4	336	3	294	2	378
6	2	336	1	378	4	210	3	420

Through MATLAB, the catastrophe genetic algorithm was used to solve the problem and compared with the traditional genetic algorithm to obtain an iterative diagram, as follows. It can be seen from the Figure 5 that the traditional genetic algorithm tends to be gentle after 20 iterations, indicating that the traditional genetic algorithm has the defect of 'precocity' and easily falls into the local optimal solution. The catastrophic genetic algorithm undergoes multiple disasters in the iterative process, which makes it easier to obtain better results by increasing the diversity of the population and jumping out of the local optimal solution.

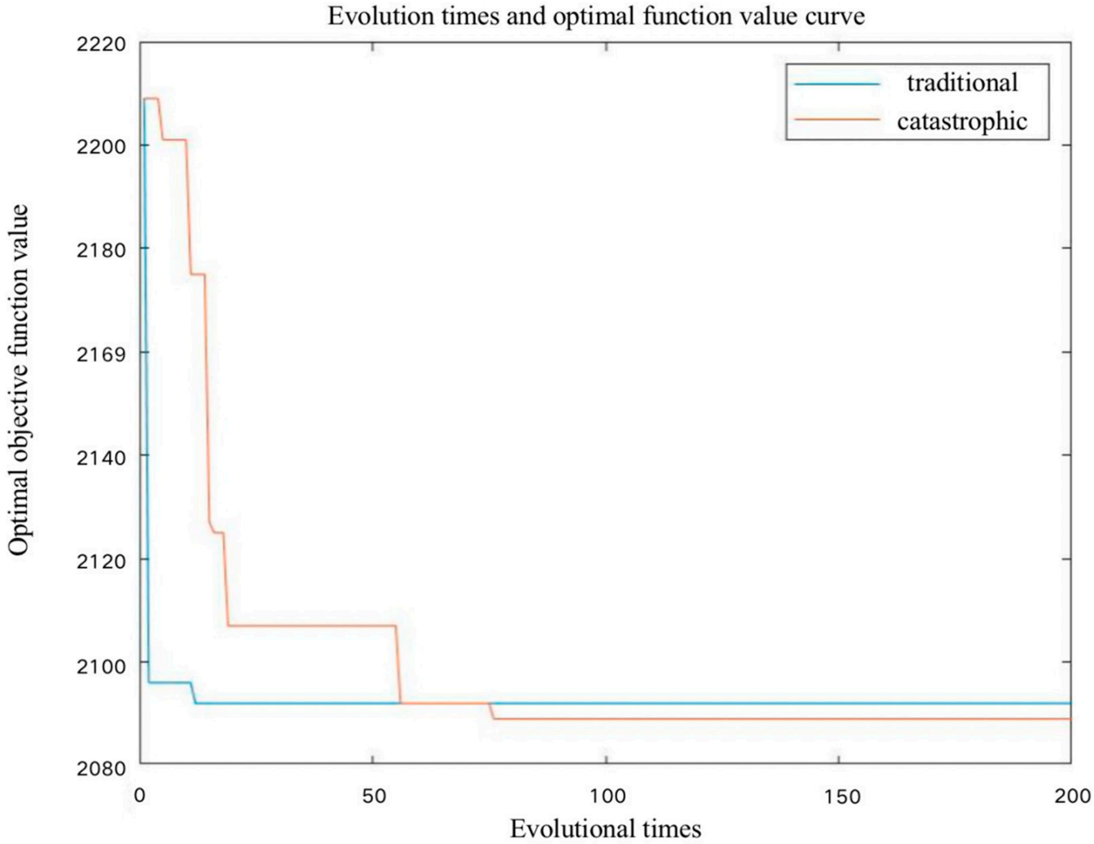

Figure 5. Evolution times and optimal function value curve.

From the results of a Gantt chart Figure 6 and program operation, it can be understood that the optimal result time was 2142 s. The processing sequence of specific equipment was illustrated by taking the No. 1 equipment as an example: the No. 1 equipment (4-1, 5-2, 2-3, 6-3, 3-4, 1-4), that is, at the beginning of production, process 1 of the No. 4 plate was first processed with the No. 1 equipment, followed by process 2 of the No. 5 plate, process 3 of the No. 2 plate, process 3 of the No. 6 plate, process 4 of the No. 3 plate, process 4 of the No. 1 plate, and so on.

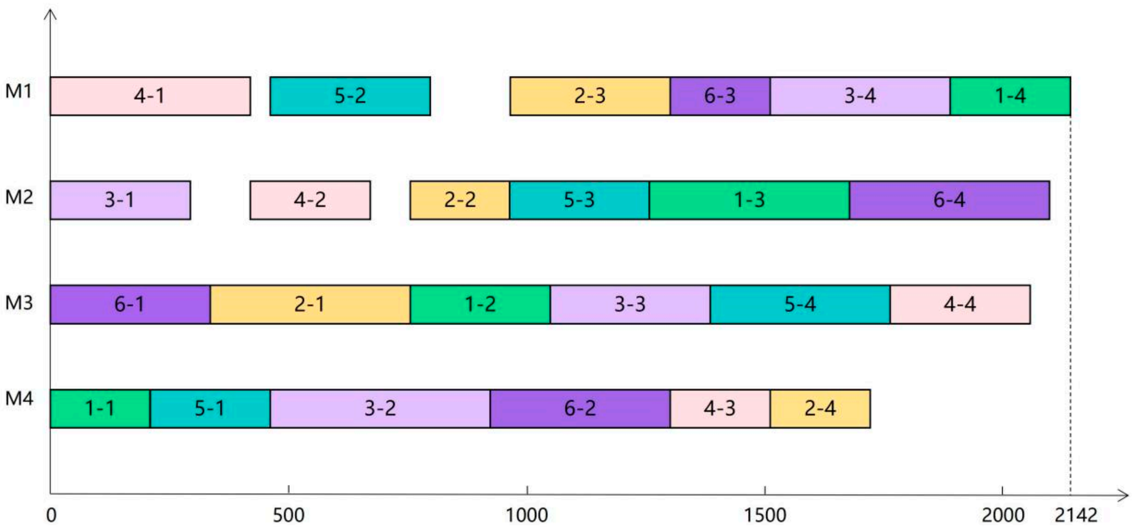

Figure 6. Initial scheduling scheme Gantt chart.

4.2. Event-Driven Dynamic Scheduling of Production Equipment Operation

From the complex event processing in Section 3, it can be understood that the production line can use the complex events of the equipment state and the RFID complex events to obtain the matrix formula (Formula (8)) of the workpiece and equipment processing state, as shown below.

$$S_{6\times 4} = \begin{bmatrix} S_{11} & S_{12} & S_{13} & S_{14} \\ S_{21} & S_{22} & S_{23} & S_{24} \\ S_{31} & S_{32} & S_{33} & S_{34} \\ S_{41} & S_{42} & S_{43} & S_{44} \\ S_{51} & S_{52} & S_{52} & S_{54} \\ S_{61} & S_{62} & S_{63} & S_{64} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 0 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \end{bmatrix} \tag{8}$$

According to the matrix formula, the processing status of the workpiece and the processing status of the equipment can be monitored in real time. According to the above formula, it can be understood that workpiece 2 exhibited an abnormal event on equipment 1. The following analysis is based on this abnormal event.

When the PCB No. 2 board is abnormal on the marking machine, it means that the marking machine has no way to further process the subsequent plate. In view of this situation, the first scheme is to wait for the marking machine to restart and correct before processing. The second scheme is to reschedule the unprocessed plate. In this paper, the selection of the two schemes is investigated. Finally, the parameters are set according to the actual experience. Assuming that the time from the equipment shutdown to restarting accounts for more than 10% of the total processing time, the second scheme is selected. If the time ratio is less than 10%, the first scheme is selected. Using an example for analysis, assuming that the delay caused by the marking machine is 70 s, the total processing time is 2142 s, and the proportion of scheduling optimization can be deemed to be 3.3%. Therefore, the first scheme was used for continuous processing, and the workpiece delay processing scheduling Gantt chart was obtained, as shown in Figure 7. It can be seen that the impact of the equipment operation event on the initial scheduling depends on the length of the delay time caused by the abnormal event.

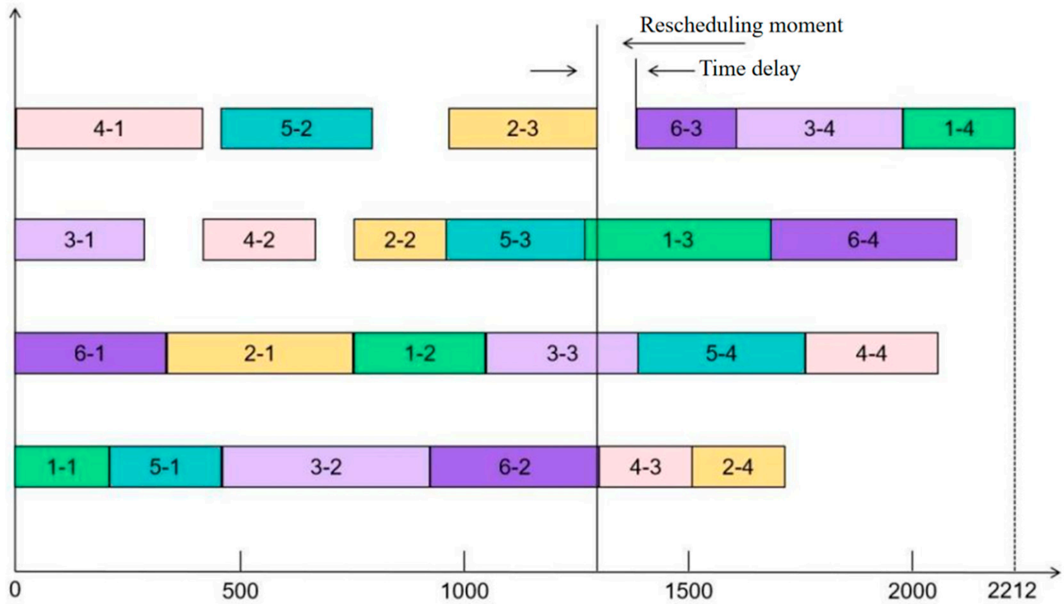

Figure 7. Gantt chart of workpiece delay processing scheduling.

4.3. Dynamic Scheduling of Event-Driven Emergency Insertion

As it is shown in Figure 8, When the PCB No. 2 board is completed by the marking machine, the experimental platform of the PCB micro-hole drilling production line monitors the occurrence of an emergency insertion event and judges that it is a new insertion of workpiece 7: J71 (M1, 480), J72 (M2, 200), J73 (M4, 380), and J74 (M3, 380). In the case of not identifying the emergency insertion event, job 7 will be processed after all jobs are processed, and the resulting scheduling Gantt chart is shown in the figure. At this time, the entire processing time is 3582 s.

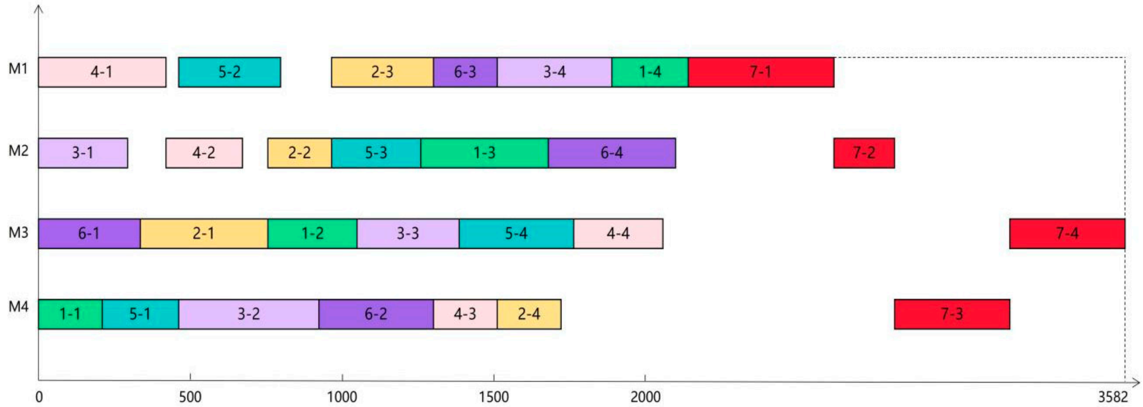

Figure 8. Dynamic scheduling Gantt chart of unidentified emergency order insertion.

If the system recognizes the emergency order insertion event and judges the priority of the plate for the emergency order insertion, it is judged that the priority of the newly inserted plate is the highest. At this time, the optimal production scheduling scheme will be obtained, and then the plate with a lower priority will be processed. In this process, it is also necessary to make full use of the idle time of the replaced plate for local dynamic optimization to obtain the optimization rate $f_2 \approx 25.1\%$, indicating that the emergency order insertion exerts a great disturbance of the initial scheduling. The minimum time for rescheduling completion was 2682 s, and the dynamic scheduling Gantt chart based on the emergency order insertion in Figure 9 was obtained. It can be seen that the newly inserted workpiece is preferentially processed on each machine. Then the unprocessed jobs in the original scheduling are processed.

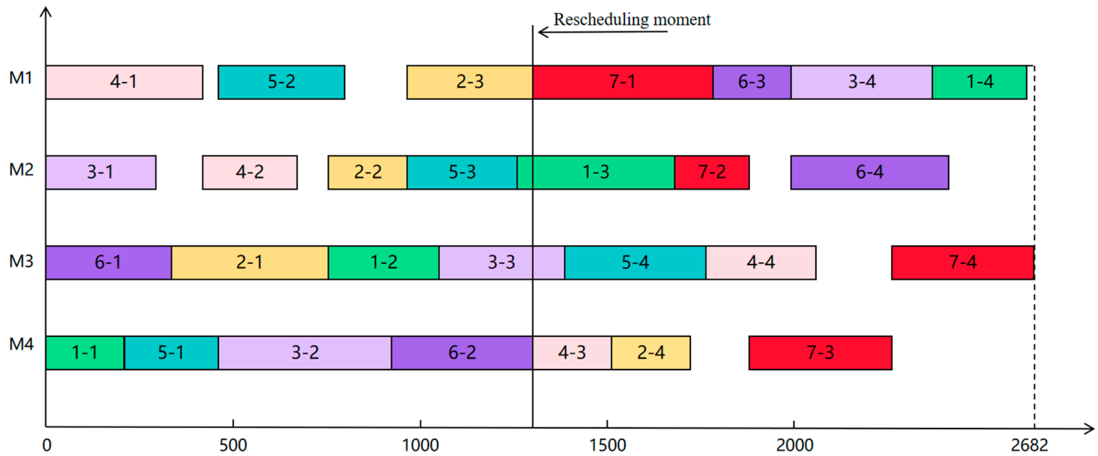

Figure 9. Dynamic scheduling Gantt chart for identifying complex events in emergency order insertion.

4.4. Tool-Failure-Event-Driven Dynamic Scheduling

In the production process of PCB in this paper, because there was only one drilling machine, only the remaining service life of the drilling machine was predicted and analyzed. In the actual production process, if multiple drilling machines are encountered, only the service life of other tools needs to be described according to the method of complex events in this paper.

According to the table and the initial production scheduling scheme, the processing time of each equipment is expressed as a matrix, and the row number is the equipment number:

$$A = \begin{bmatrix} J_{41} & J_{52} & J_{23} & J_{63} & J_{34} & J_{14} \\ J_{31} & J_{42} & J_{22} & J_{53} & J_{13} & J_{64} \\ J_{61} & J_{21} & J_{12} & J_{33} & J_{54} & J_{44} \\ J_{11} & J_{51} & J_{32} & J_{62} & J_{43} & J_{24} \end{bmatrix} = \begin{bmatrix} 420 & 336 & 336 & 210 & 378 & 252 \\ 294 & 252 & 210 & 294 & 420 & 420 \\ 336 & 420 & 294 & 336 & 378 & 294 \\ 210 & 252 & 462 & 378 & 210 & 210 \end{bmatrix} \quad (9)$$

From the tool failure event in the third chapter, it can be understood that the monitoring event of the current tool processing state can be expressed as $RUL_b = e_b$ (2, PCB002,800,0). This event indicates that the remaining service life of the drill bit with the ID of PCB002 on the drilling machine was expected to be 800 s, and the tool belonged to the normal processing situation. However, in order to ensure smooth processing, the micro drill can be replaced in advance to avoid the interruption of the tool during the machining process.

This paper assumes that the time to replace the micro drill is 20 s. At present, the PCB micro-hole drilling production line monitors the drilling machine in the processing of PCB No. 6 according to the complex events of the production state and judges that the drilling machine has been processed for 185 s. At this time, the remaining tool life is 800 s. The system actively predicts the time to replace the micro drill. From the matrix, we can confirm that the drilling machine enters a new processing cycle after the completion of J64, and the processing time is 294 s, 252 s, 210 s, 294 s, 420 s, and 420 s.

In the case of not identifying the remaining service life of the tool, Figure 10 is obtained, when the J22 processing is carried out to 61 s, the tool fails, and the workpiece 2 is scrapped. At this time, the tool change operation is performed. If rescheduling is not performed, the J21 processing is performed again after the J12 processing is completed. In this case, the scheduling time is 2856 s.

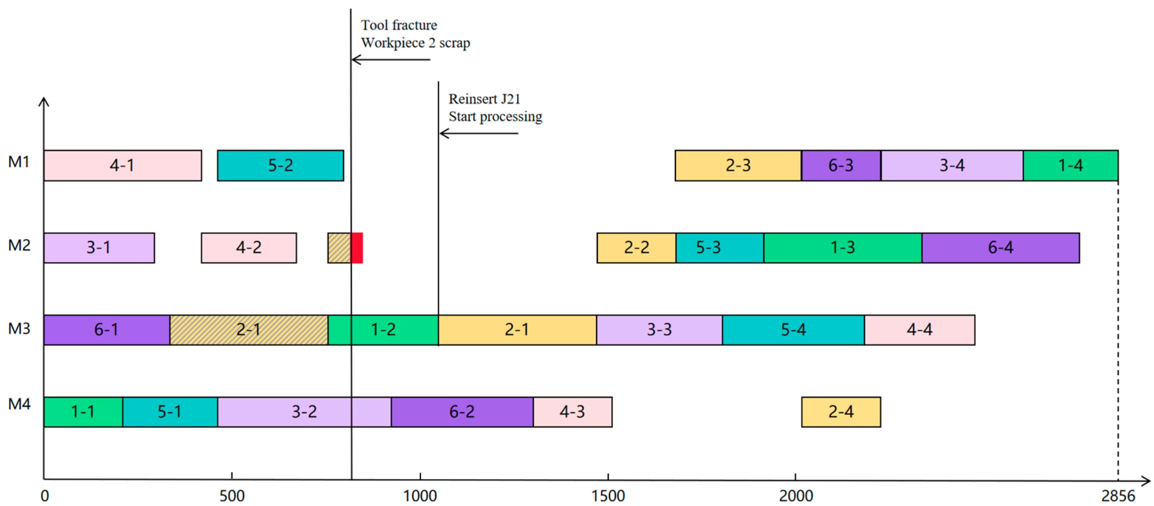

Figure 10. Scheduling Gantt chart of unidentified tool failure events.

If dynamic rescheduling is performed immediately after the tool change is completed, the new scheduling Gantt chart is obtained without waiting to process other workpieces directly. As it is shown in Figure 11, at this time, the whole machining process takes 2646 s.

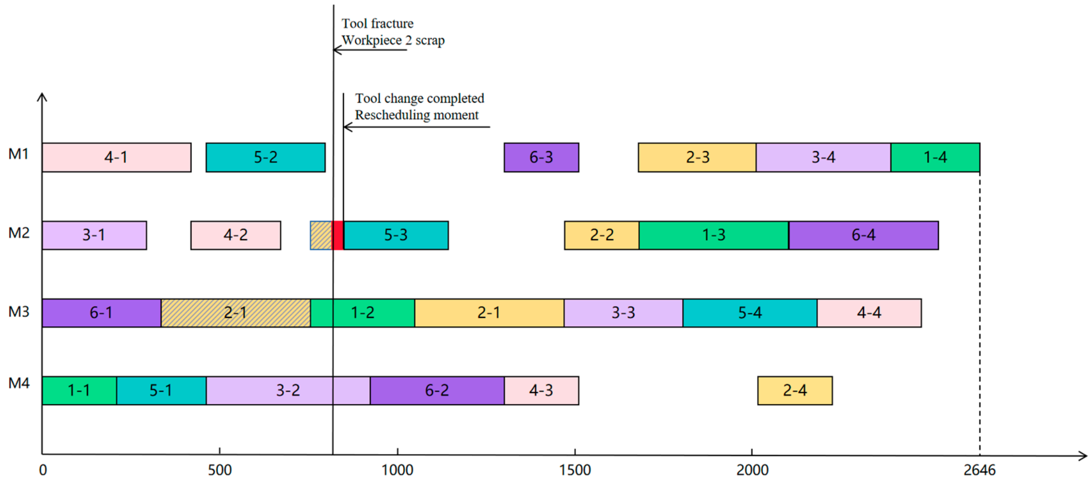

Figure 11. Dynamic rescheduling Gantt chart of unidentified tool failure events.

If the remaining service life event of the tool is known, it can be concluded that the time to change the drill is after the completion of J64, before the start of processing of J31, before the start of processing of J42, and after the completion of processing of J42. The corresponding remaining life is 565S, 313S, 313S, and 61S, and the result of calculating the idle time is greater than the drill change time of 20S. Therefore, it is best to choose to change the drill in these four time periods, which means that it is most suitable for the drill to change the tool after processing this cycle or in the middle of the next cycle, and it will not have any impact on production scheduling. If other time periods are selected for changing the drill, it will affect the normal operation of production scheduling. Therefore, the optimal scheduling Gantt chart is shown in Figure 12. Compared to the processing time when complex events are not identified, the optimization rate at this time is $f_2 = 25\%$, and the disturbance has no effect on the initial scheduling. Therefore, the prediction of the remaining useful life of the tool can change the tool before the tool's failure, which can reduce the time of the whole production scheduling and improve processing efficiency while avoiding the scrapping of the workpiece.

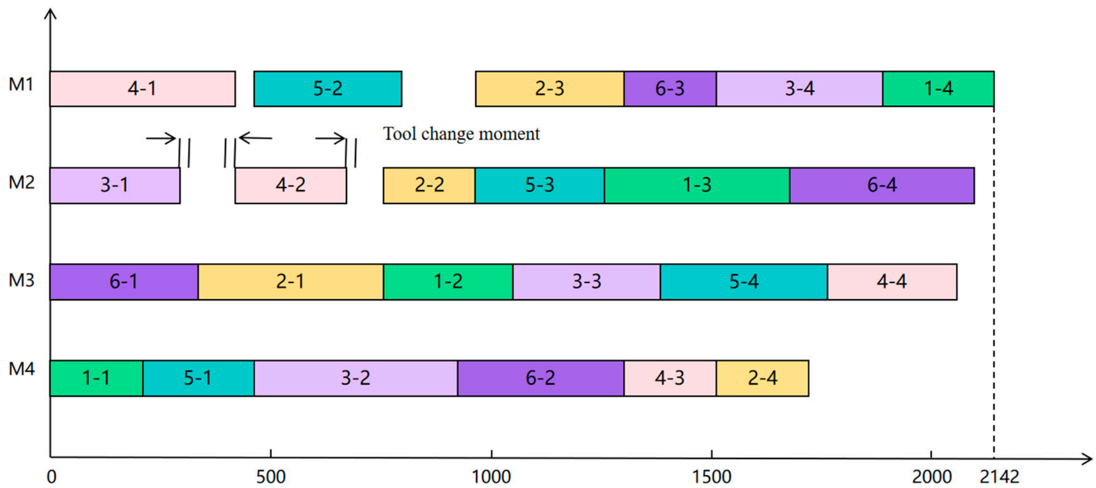

Figure 12. Dynamic scheduling Gantt chart for identifying tool failure events.

The scheduling time of the equipment operation event needs to be calculated according to the time spent waiting for the equipment to restart, which does not reflect the specific value in Table 2. However, it can be seen from whether the emergency insertion event and the tool failure event in Table 3 identify the scheduling time of the complex event that the dynamic scheduling time after identifying the complex event is significantly less than the scheduling time when the complex event is not identified. The identification of complex events can improve the production efficiency of a PCB micro-hole drilling production line. In addition, in the tool failure event, the production time of rescheduling immediately after a tool change is shorter than that of continuing processing after waiting for a tool change.

Table 2. Comparison table of scheduling times and completion times under different conditions.

	Whether Complex Events Are Identified	Time to Finish Work (s)
Equipment operation events	No	2142 + device recovery time
	Yes (delay proportion less than 10%)	
	Yes (delay proportion more than 10%)	Reschedule immediately

Table 3. Comparison table of scheduling times and completion times under different conditions.

Event Name	Whether Complex Events Are Identified	Time (s)	Optimization Rate
Emergency insertion event	No	3582	25.1%
	Yes	2682	
Tool failure event	No (continue processing after tool change)	2856	25% (continue processing after tool change) 19% (rescheduling immediately after tool change)
	No (rescheduling immediately after tool change)	2646	
	Yes	2142	

5. Conclusions

Aiming at the key challenges in PCB micro-hole drilling production lines, this paper has established three complex event models: an emergency insertion event, a production line equipment operation event, and a tool failure event. Based on complex events, combined with the initial scheduling optimization results of the catastrophic genetic algorithm, the dynamic scheduling of the production line was realized. The conclusions are as follows.

The simulation results of the initial scheduling of a PCB micro-hole drilling production line show that the catastrophic genetic algorithm has a higher number of iterations than the traditional genetic algorithm, can avoid falling into the local optimal solution, and has better recognition and better decision-making ability. It is more accurate and effective than the traditional genetic algorithm in solving complex-event-driven production scheduling problems, and it provides accurate and effective solutions for various production line scheduling problems.

Three complex event models of an emergency insertion event, a production line equipment operation event, and a tool failure event have been established. Dynamic scheduling optimization is carried out when the above complex events occur in a production line. The results show that the scheduling optimization rate can reach 25.1% after the emergency insertion event is identified. The scheduling optimization rate of a production equipment operation event is related to the specific failure time of equipment. The scheduling optimization rate can reach 25% after the tool failure event is identified. Rescheduling immediately after the tool failure event is identified can have no effect on the initial scheduling process.

There are multiple events that occur at the same time in the micro-hole drilling production line of a PCB, so the dynamic scheduling of multiple events can be studied in the future.

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