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# Research and Application of Bottleneck-based Planning and Scheduling Method for PCB Manufacturing System

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**Abstract.** Researches on planning and scheduling of PCB production system are gaining more and more attention due to the complexity and uncertainty of it. Current research focused on the solving method how to make better schedule solution for PCB system based on a real case of PCB production enterprise. Firstly, for the bottleneck process of electroplating, a mixed integer programming model is proposed, moreover, a branch and bound method is employed to solve the problem. Secondly, for non-critical processes, the man-hour quota is predicted using the neural network model and the association rules, and then the data can be found using the association rules and be modified. Thirdly, the planning and scheduling method based on bottleneck is used for the order sequencing, and “pull-push” mechanism of Drum-Buffer-Rope are applied to generate the scheduling scheme for non-bottlenecks. In the end, the effectiveness of the proposed scheduling method is proved by computational experiments.

## 1. Introduction

With the rapid development of electronic communication technology, the market demand of printed circuit board (PCB) is greatly increasing. Due to the complexity of PCB production process, the variety of products and the uncertainty factors, it is very difficult to make production plan for PCB production. With the intensification of competition, more and more attention has been paid to the formulation of production plan for PCB manufacturing system.

There are many literatures about scheduling problem in PCB manufacturing system. However, most studies only focus on scheduling of single processor or workstation, such as sorting scheduling of surface mounting equipment [1] and grabbing scheduling of electroplating workstation [2]. Very few researches are about the overall production schedule of PCB manufacturing system. Kim et al. [3] proposed a heuristic algorithm for PCB assembly systems, but their research is limited to typical



(non-hybrid) flow shop scheduling problems. Referring to the semiconductor wafer planning method, PCBs planning can use or modify various scheduling methods or rules, such as Dessouky and Leachman [4], Kim [5] and Dabbas [6].

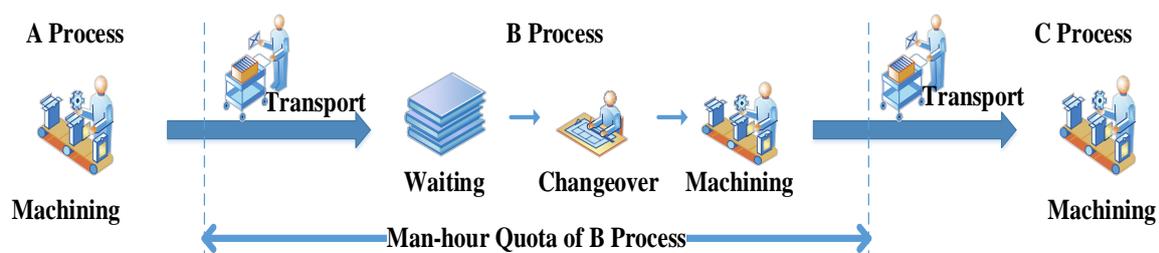
In summary, it is of great significance both in academia and industry to study the production plan of PCB workshop. This paper is devoted to optimizing the bottleneck production planning schedule and forming the overall production plan of PCB workshop, so as to achieve the goal of improving the productivity and efficiency of PCB workshop.

## 2. Description

There are various logic of series, parallel and reflux in the process flow of PCB workshop. If all processes are considered in a same production scheduling level, as a result, the scheduling model will be super big with high computational complexity. Therefore, several key processes are selected out, and only the sequence of critical processes is carried out in production scheduling. According to historical data, automatic optic inspection (AOI), oxide replacement, lamination, drilling, electroplating, welding resistance and final inspection are selected as critical processes. In the critical process, electroplating is the bottleneck. The processes which are not belong to critical process are non-critical processes.

In current research, bottleneck process problem, i.e. electroplating scheduling problem, is summarized as a parallel machine scheduling problem with shared hoists, which can be summarized as follows. Consider the problem that  $N$  tasks are processed on  $M$  parallel electroplating tanks.  $M$  parallel electroplating tanks share the same hoists, as shown in figure 1. This paper has the following assumptions: (1)  $N$  independent workstations are non-preemptive and are processed in parallel processor units; (2) The operation cycle of the hoist is  $T$ , the unloading time is  $T$ , and the loading time is 0, but the loading time is  $T$  when continuous loading; (3) All the hoist and electroplating tanks are idle at 0 time; (4) The shared hoist and the electroplating tanks can only handle one task at a time; (5) The time for the hoist to each electroplating tank is the same; (6) The hoist and electroplating tanks will not break down.

In order to avoid the tedious and lengthy formulation of production plans, the man-hour quota is used instead of the standard processing time to calculate the processing time of production in non-critical processes. It is called the man-hour quota of the process from the entry of the task to the completion of the processing of the order. It includes the basic processing time, auxiliary time, layout time, rest time and so on, as shown in Figure 1.



**Figure 1.** Diagram of man-hour quota

### 3. Production planning method

#### 3.1 Bottleneck process scheduling optimization based on branch and bound method

3.1.1 Model parameters and constraints. The basic parameters are shown as following.

$N$	Number of work tasks
$M$	Number of parallel electroplating tank
$T$	Cycle time of shared hoist
$PT_i$	Processing time of working task $i$
$SH_k$	Starting time of the $k$ th activity of the hoist, $k = 1, 2, 3, \dots, 2N$
$C_{max}$	Completion Time
$\Omega$	Maximal value

Decision variables:

$$x_{ijk} = \begin{cases} 1, & \text{If the } k\text{th activity of hoist is to load task } i \text{ into tank } j \\ 0, & \text{otherwise} \end{cases}$$

$$y_{ijk} = \begin{cases} 1, & \text{If the } k\text{th activity of hoist is to unload task } i \text{ from tank } j \\ 0, & \text{otherwise} \end{cases}$$

Objective function and constraints:

$$\text{Min } Z = C_{max} \quad (1)$$

s t :

$$C_{max} \geq SH_{2N} + T \quad (2)$$

$$\sum_{j=1}^M \sum_{k=1}^{2N} x_{ijk} = 1; \quad \forall i = 1, 2, \dots, N \quad (3)$$

$$\sum_{j=1}^M \sum_{k=1}^{2N} y_{ijk} = 1; \quad \forall i = 1, 2, \dots, N \quad (4)$$

$$\sum_{j=1}^M \sum_{i=1}^N (x_{ijk} + y_{ijk}) = 1; \quad \forall k = 1, 2, \dots, 2N \quad (5)$$

$$\sum_{k=1}^{2N} x_{ijk} = \sum_{k=1}^{2N} y_{ijk}; \quad \forall i = 1, 2, \dots, N, \quad \forall j = 1, 2, \dots, M \quad (6)$$

$$\sum_{k=1}^{k'} \sum_{j=1}^M x_{ijk} \geq \sum_{k=1}^{k'} \sum_{j=1}^M y_{ijk}; \quad \forall i = 1, 2, \dots, N, \quad \forall k' = 1, 2, \dots, 2N \quad (7)$$

$$SH_{k+1} \geq SH_k + \sum_{j=1}^M \sum_{i=1}^N \sum_{j'=1}^M \sum_{i'=1}^N \left[ T \cdot y_{i'j',(k+1)} + T \cdot x_{ijk} \cdot x_{i'j',(k+1)} \right]; \quad \forall k = 1, 2, \dots, \quad (8)$$

$$SH_{k+1} \geq SH_l + \sum_{i=1}^N \left[ \left( \sum_{j'=1}^M \sum_{i'=1}^N T \cdot x_{i'j',(l-1)} + PT_i \right) \cdot x_{ijl} + T \right. \\ \left. \cdot y_{ijl} \right] + \Omega \left[ \sum_{i=1}^N (x_{ijl} + y_{ijl} + x_{ij,(k+1)}) - 2 \right]; \forall k = 1, 2, \dots, 2N-1, \forall l = 1, 2, \dots, k, \forall$$

$$x_{ijk} \in \{0, 1\}; y_{ijk} \in \{0, 1\}; \forall i = 1, 2, \dots, N, \forall j = 1, 2, \dots, M, \forall k = 1, 2, \dots, 2N \quad (10)$$

The model takes the activities of the hoist as decision variables, and  $N$  tasks correspond to  $2N$  activities of the hoist. Equation (1) indicates that the model aims at minimizing the completion time. Constraint (2) is about the completion time and the hoist. Constraint (3) and (4) indicate each task is loaded and unloaded only once. Constraint (5) ensures the hoist can only handle one task at a time. Constraint (6) means that the corresponding electroplating tanks are the same for each task loading and unloading. Constraint (7) describes that the task can only be loaded before unloaded. Constraint (8) shows the constraint relationship between two adjacent start times. Constraint (9) means the constraint of the release time of the electroplating tank. Constraint (10) is constraints about decision variables and parameters.

*Algorithmic logic of branch and bound:*

Step 1: A preliminary scheduling result can be obtained by using MSPT algorithm, and the total completion time of the scheduling is taken as the upper bound (UB). Let  $r = 0$ , the corresponding  $R(r)$  be empty, and the branching process starts at node 0.

Step 2: Deciding on possible branches. When a node is selected, the unscheduled work  $J_r$  and empty processor can be figured out. If there are empty processor and unscheduled jobs, the number of jobs to be scheduled is the range of possible loading choice (PLC), otherwise PLC=0. If the processor is not empty, the number of jobs on the processor is the range of possible unloading choice (PUC), otherwise PUC = 0. Therefore, the possible branch (PB) of a node is equal to the sum of PLC and PUC. Let  $R(r+1) = R(r)$  and add 1 in turn.

Step 3: Calculate the lower limit. The earliest starting time of processor is calculated by REST algorithm. STPT rule and the m-jobs-at-a-time assignment procedure can be used to determine the scheduling order. The lower limit of completion time is calculated by formula (1) and (2). Repeat until all branches are computed. Compare the lower limit of each node with UB and eliminate the remaining nodes. If  $r = 2n - 1$ , go to step 5, otherwise go to step 4.

Step 4: Select branches. Select a node with a minimum lower bound, update its corresponding  $r$  and  $R(r)$  values, and go back to step 2.

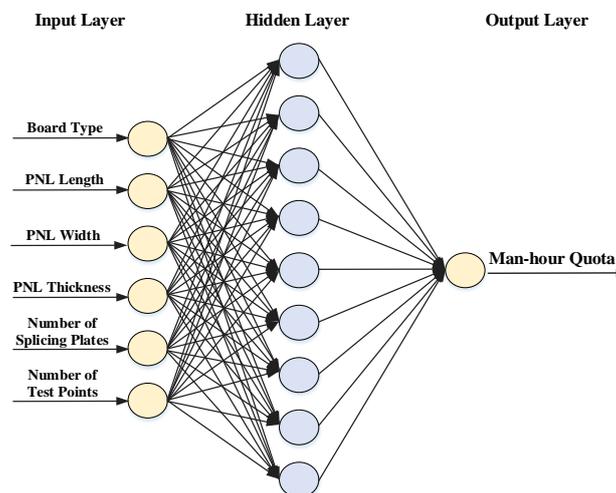
Step 5: Measurement process. UB is replaced by the value of the new solution. Other nodes with lower bounds greater than or equal to UB will be deleted. If all the nodes have been measured, an optimal solution will be obtained; otherwise, return to step 4.

### 3.2 Prediction and analysis of man-hour quota of non-critical processes based on BP neural network and association rule analysis

This paper analyses the man-hour quota of non-critical processes in PCB workshop by using big data, data mining and other technologies. First, the BP neural network prediction model is adopted to

preliminarily predict the man-hour quota of orders in different processes. Then the association rules are used to find out the process needed to be revised, and revise it.

*3.2.1 Prediction of man-hour quota based on BP neural network model.* Back Propagation (BP) network, well-known neural network models nowadays, is a multi-layer feedforward network trained by error back propagation algorithm. Because the influencing factors and weights of different processes are different, it is necessary to establish different prediction models for different production processes. Current study takes electronic testing as an example to describe the process of building neural network prediction model. The BP neural network model of man-hour quota prediction for electronic testing is shown in the Figure 2, which consists of three layers: input layer, hidden layer and output layer. The input layer includes six attributes, such as board type, PNL length. The predicted value of the man-hour quota of the output layer is obtained by processing nine nodes of the hidden layer.



**Figure 2.** BP Neural Network Model for Forecasting Man-hour Quota

*3.2.2 Modify of prediction results based on association rule Apriori algorithm.* The steps of Apriori algorithm are as follows:

Step 1: Find frequent item sets  $I$ . By counting the occurrence times of all elements in  $I$ , the item sets less than the minimum support count threshold  $\text{min\_support}$  are screened out, and the remaining frequent item sets are recorded as set  $L_1$ .

Step 2: Connection. If two frequent  $k - 1$  item sets ( $I_1, I_2$ ) can be connected, a new  $k$  item set is generated from them. All sets that may be composed of frequent item sets  $k$  are denoted as  $C_k$ .

Step 3: Pruning. To screen  $C_k$ , if all  $k-1$  subsets of each candidate item set  $k$  are preserved in  $L_{k-1}$ , otherwise deleted. The frequency of all item sets in  $C_k$  is counted, and the set  $L_k$  is obtained by deleting those less than  $\text{min\_support}$ .

Step 4: Repeat step 2 or 3 until find  $k$  that  $C_k = \emptyset$ , obtain all frequent item sets.

This paper uses Python language to implement Apriori algorithm. The parameters in the algorithm are: minimum support is 0.3, minimum confidence is 0.5. After running, all association rules with 1 consequent are obtained. According to the obtained association rules, the records that need to be

revised are found. The revise method is as follows:

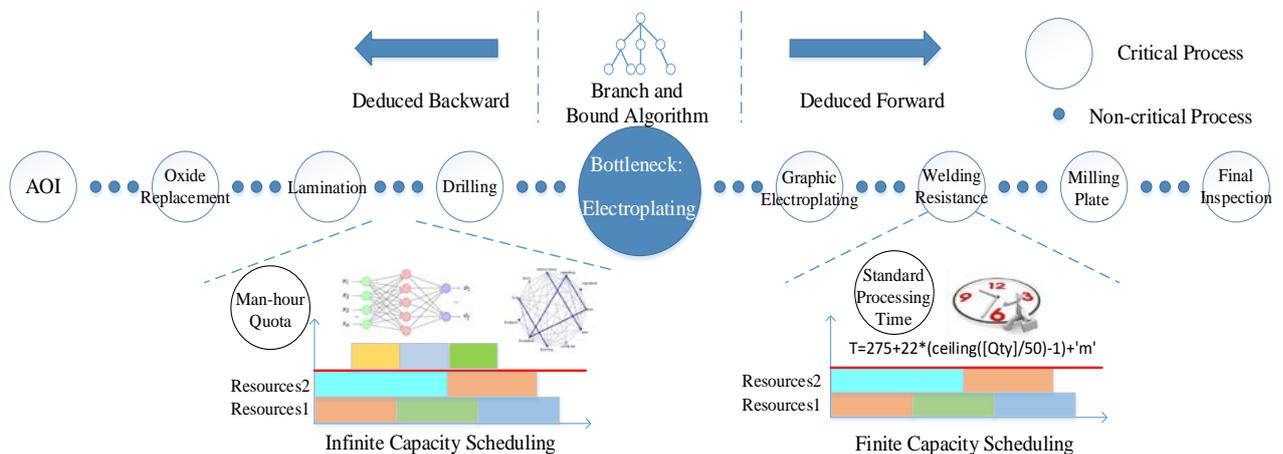
$$T_r = T + a_i \times (\bar{T} - T) \#(11)$$

$T_r$  is the revised man-hour quota,  $T$  is the original man-hour quota,  $\bar{T}$  is the average value of the predicted man-hour quota that satisfies the association rule in all records,  $a_i$  is the confidence under the association rule.

### 3.3 Bottleneck-based integrated production scheduling method for PCB workshop

In the current research, we use Hibernate framework with Java language and MySQL database to realize the overall scheduling method of PCB workshop. We use Java algorithm and heuristic scheduling rules to drive data and arrange production. The final scheduling results are output in the form of task data.

Firstly, according to the resource load rate, the processes are divided into two categories: critical process and non-critical process. Secondly, the branch and bound algorithm is used to arrange the production of bottleneck process (electroplating process) so as to maximize the utilization of resources, and the order sequence of electroplating process is guaranteed by setting time buffer. Then using heuristic rules, the production plan after the bottleneck process can be deduced forward, and the production plan before the bottleneck process can be deduced backward. The processing time of critical processes is calculated by standard processing time, but non-critical processes' by man-hour quota. Finite capacity scheduling is used for critical processes and infinite capacity scheduling for non-critical processes. Through the above steps, we can get the planned starting time and ending time of each process of all orders, and the processing equipment of each critical process of orders. To sum up, the whole process of production scheduling is completed, as shown in Figure 3.



**Figure 3.** The Diagram of the Whole Production Scheduling in PCB Workshop

## 4. Experimental results

### 4.1 Scheduling optimization results of bottleneck process

Taking 100 orders as an example, branch and bound algorithm and genetic algorithm are used to optimize bottleneck process scheduling by the same encoding method, and the results are compared as shown in table 1.

**Table 1.** Experimental results of branch and bound comparison with genetic algorithm

Processing time	40, 100, 120, 140, 160	Branch and bound algorithm			Genetic algorithm		
		Parameter	Runtime	Makespan	Parameter	Runtime	Makespan
Number	Experiment 1	10	215.9	753.8	50	2725.4	754.8
	40, 25, 10, 15, 10	50	810	748.8	100	5745.4	752.4
	Experiment 2	10	205.5	734.6	50	2814.1	736.6
	40, 30, 10, 15, 5	50	655.5	732.8	100	5863.5	734.6
	Experiment 3	10	178.1	778.6	50	2723.1	785.2
	30, 30, 20, 15, 5	50	621.4	778	100	5818.5	783
	Experiment 4	10	263.3	719.6	50	2814.1	719
	50, 15, 20, 5, 10	50	838.8	715	100	5916.1	718.2
	Experiment 5	10	179	862.8	50	2704	869.6
	20, 25, 20, 25, 10	50	704.2	860.4	100	5619.5	868

The unit of runtime in the table is milliseconds. In branch and bound algorithm, the parameter represents the number of solutions generated randomly each time. Node cleaning is performed every 50000 times, and the first 100 items are retained each time. In genetic algorithm, the parameter represents the population size, and the reproductive algebra are 1000. The result of makespan is the average result of 10 runs under this parameter. From the results, it can be seen that the branch and bound algorithm is slightly better than the genetic algorithm for each case, and the runtime is much lower than the genetic algorithm.

#### 4.2 Prediction and analysis results of man-hour quota for non-critical processes

There are four main parameters in the neural network model, learning factor, momentum factor, training times and allowable errors. By the methods of control variables and cross-parameter experiments, the accuracy is the highest when the training times are 1000, the allowable error is  $1.00E-07$ , the learning factor is 0.1 and the momentum factor is 0.1.

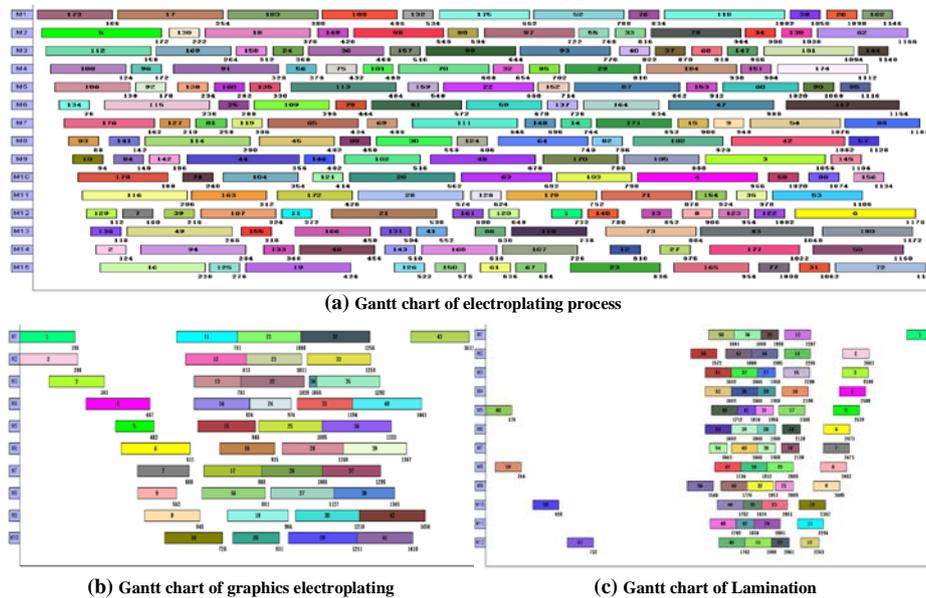
**Table 2.** Cross-parameter experiment of learning factor and momentum factor

Process	Electronic testing	Milling plate	Graphic electroplating
Unrevised	64.0%	63.7%	63.0%
Revised	73.39%	78.61%	70.59%

Experiments on different processes with this parameter show that the performance is better and stable. Therefore, all experiments are carried out according to this set of parameters. The Apriori algorithm is used to obtain the association rules. Thus, the forecast results of man-hour quota can be modified according to the modified rules. After modifying, the accuracy of electronic testing prediction reached 73.39%, as show in table 2. In addition, this method is used to analyze the milling process and graphic electroplating, and the accuracy is 78.61% and 70.59% respectively. Therefore, this method is considered to be effective and feasible.

### 4.3 Results of overall production scheduling in PCB workshop

In this paper, the example of production scheduling experiment is carried out by taking the orders of one day in actual production. The results of production scheduling are shown in Figure 4.



**Figure 4.** Gantt charts of scheduling results

## 5. Conclusion

Current research studied the planning and scheduling method for a real PCB production system in Guangzhou China. A mixed integer programming model is built for electroplating process which is the bottleneck of the system. A branch and bound method is adopted to optimize its sequence. Furthermore, current paper proposed a method based on BP neural network and association rule analysis to predict the man-hour quota of non-critical processes. Experimental results indicate that the proposed scheme can optimize the sequence of bottleneck effectively and predict the man-hour quota accurately. Based on the optimal scheduling on bottleneck and accurate prediction of man-hour quota in non-critical processes, the suitable scheduling results of the whole PCB system can be figured out rapidly. In future, there are several directions needed to do more in-depth investigations. For example, it's necessary to improve prediction accuracy. Also it needs developing intelligent algorithms and making more experiments to improve the solution much better.

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