

Uniform Design Research for Maintenance Strategy of Automatic Production Line

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ABSTRACT: Classification of equipment is the main method in group maintenance model for automatic production line. Equipment with different importance should be assigned different maintenance strategies. But method of division importance of equipment is not mature, most of the literature only considered downtime. In order to maximize the production rate, we simulate the actual production line, consider the layout, production time, buffer condition of the production line, find the relationship between production rate and failure rate, repair rate by uniform design method. Find the failure rate and repair rate indicator which have a great impact on the production rate with stepwise regression method and find critical equipment, take different maintenance strategies for equipment which have different importance. Finally verify the correctness of the model. This paper simulates the actual situation of the production line, has relatively few subjectivity and a certain reference value for the maintenance policy of production line.

Keywords: Automatic Production Line, Equipment Reliability, Uniform Design, Stepwise Regression

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1. Introduction

Automatic production line is an important part of the production system, but reliability and maintainability of most equipment are poor, downtime costs caused by equipment failure become a heavy burden of enterprise. According to the survey, maintenance costs of manufacturing automatic production line equipment account for 10% to 30% of revenue, downtime rate reached 14.8%.

Currently research for maintenance strategy of equipment is more mature, but maintenance strategy of automatic production line requires further discussion.

Domestic and foreign scholars have established some maintenance strategy model of the production line. Most use Group Maintenance Policy(GMP), replace a set of part, multiple devices periodically, maintain multiple equipment at one time[1]. Rao et al[2] proposed Opportunity Maintenance(OM), when a machine fails in production line, maintain the remaining equipment during this time. Christer, professor Weibin Wang proposed delay time models[3], through Preventive Maintenance(PM) prevent production losses caused by equipment failure when the device deteriorated. Delay time model can determine preventive maintenance cycle of the equipment, provide a new theoretical approach for the maintenance strategy of production line. Zheng Rui, Lv WenYuan[4] reference delay time model theory, determine the automatic production line synchronization maintain model that can obtain the best preventive maintenance cycle of the equipment. Lv WenYuan, Zhang Xinbo[5] et al take the constraints of the maintenance costs into account, proposed synchronization maintain model of production line based on the “maintenance costs - reliability”. The 80/20 rule is used in the model, down time of equipment is sorted in descending order, the top 20% equipment require preventive maintenance. But it is not comprehensive to select significant equipment only through down time. Kong FanSen[6] divide the equipment into four grades such as unimportant , general, important, very important with extension analysis method. different maintenance strategies are introduced into different grades. But there is certain subjectivity in this method. Huang YongQing[7] et al optimize the parameters of the ant colony algorithm with uniform design method, get the desired results with fewer numbers of experiment. Although it cannot test factors in each level by uniform design method, as the pilot point dispersed uniformly, it prove that is very effective through a lot of tests[8-10]. In this paper, we maximize the production rate, establish a simulation model based on the actual situation of the production line, simulate the production line with Uniform Design Method. Through the impact of each maintenance index on production rate, determine the importance grade of equipment on productive factor, different maintenance strategies are introduced into equipment with different importance. This method can simulate the actual situation of the production line, it has less subjectivity and a certain rationality.

2. Uniform Design Research for Maintenance Strategy of Production Line

Breakdown Maintenance, Preventive Maintenance, Improvement Maintenance, Status Maintenance and Opportunity Maintenance are commonly used maintenance strategies by automatic production line. There are many equipment on production line, it seems more reasonable that different maintenance strategies introduced into equipment with different importance. In this paper, we maximize the production rate, study the impact of each maintenance index on production rate with uniform design method, find factors which have greater influence on production rate, determine the key equipment. There are many factors affecting the production rate of the production line, such as the frequency of failures, repair time, buffer, the balance of production line, and so on. Because the structure of production line is complex, there are no specific relations between these factors and production rate currently. From the viewpoint of maintenance, it can impact failure rate and repair rate while improving maintenance level, so set failure rate and repair rate as research objectives.

Let us consider a transfer line consisting of K machines ($M_1, M_2, M_3, \dots, M_K$) separated by $K-1$ buffers ($D_1, D_2, D_3, \dots, D_{K-1}$). Parts flow from outside the system to machine M_1 , then to buffer D_1 , then to machine M_2 , and so forth until it reaches machine M_K , after which it leaves the system. We assume that there are always parts available at the input of the system and spaces available at the output of the system. The intermediate buffers are each of finite capacity ($L_1, L_2, L_3, \dots, L_{K-1}$). A K machine transfer line is shown in Figure 1.

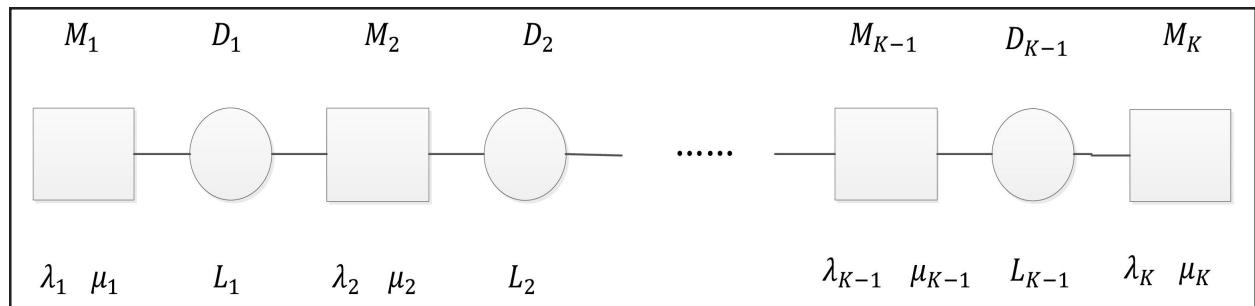


Figure 1. A transfer line with K machines

Let λ_i ($i = 1 \dots k$) be the failure rate of machine M_i . Suppose working time between failures (TBF) and time to repair (TTR) of each device are exponentially distributed, it means time to failures (MTTF) is thus $1/\lambda_i$. Since we consider operation dependent failures. After a machine has failed, it is under repair. Let μ_i ($i = 1 \dots k$) be the repair rate of machine M_i . It means time to repair (MTTR) is therefore $1/\mu_i$. Production rate (Y) is calculated as follows:

$$Y = \frac{\text{tact} \times \text{yield}}{\text{configuration time}} \quad (1)$$

To study the effect of λ_i and μ_i on production rate, we need carry out experiments on each combination of λ_i and μ_i , get the production rate on each level. For a production line with four machines, the number of parameters (s) is 8, if we take five representative values within the range of parameters ($n = 5$), carry out experiments on each level, the total number of experiments is $n^s = 625$. If the number of equipment is larger, the number of tests will be even bigger. Uniform distribution theory is used in uniform design while selecting test point, number theoretic method is used to test whether points spread very uniform within the integration range. The idea is to remove enough “uniform”, more representative test points, complete the goal on the basis of reduce the number of tests. Compared to the orthogonal design, uniform design is more suitable for multi-factor, multi-level tests. The results need to deal with regression analysis. Regression analysis can help us find important, secondary factors among many factors affect a variable when select the important equipment. Steps to determine the affect of failure rate and repair rate on production rate with uniform design method are as follows:

- (1) Collect fault data, the actual layout, the processing time of machine $M_i(T_i)$, buffer of the production line, calculate λ_i and μ_i of production line.
- (2) Determine the range of λ_i and μ_i
- (3) Take n levels for each parameter (in uniform design, n generally take 3~5 times larger than s), choose the appropriate uniform design table $U_n(n^s)$, carry out experiments in accordance with each level of the table, record production rate on each level.
- (4) Take multiple regression analysis for experiments result, find factors which have greater influence on production rate, thus screen out important equipment.

3. Simulation Experiments and Multiple Regression Analysis

Because there are no specific relations between these factors and production rate, we use simulation method. Plant Simulation is a simulation software designed by Siemens, it can build model of the plant or production line, simulate and optimize the actual production situation. Establish actual model of production line in the software, input buffer, the processing time, failure rate, repair rate determined by uniform design and output production rate of each level from the software.

Regression analysis can find the appropriate mathematical expressions between the independent variables and dependent variables while there is no strict, deterministic functional relation. It can also find important factors and secondary factors and the relationship between them among many factors which can affect a variable. Multiple regression analysis is regression analysis method study the relationship between a number of variables. In this paper, we study the relations between production rate and failure rate, repair rate. It belongs to regression analysis of multiple independent variables to a dependent variable(referred to as “one to many” regression analysis). Assume that there is no interaction relationship between various factors, the paper analyzed by linear regression.

For the above uniform test, the multiple regression model is:

$$Y = a + b_1\lambda_1 + b_2\lambda_2 + \dots + b_k\lambda_k + c_1\mu_1 + c_2\mu_2 + \dots + c_k\mu_k \quad (2)$$

Among it, the dependent variable (Y) is production rate, $\lambda_1, \lambda_2, \dots, \lambda_k$ and $\mu_1, \mu_2, \dots, \mu_k$ are independent variables, $a, b_1, b_2, \dots, b_k, c_1, c_2, \dots, c_k$ are parameters of regression equation.

We fit sample regression equation minimum mean square error method for n measured sample data $(y_i, \lambda_{i1}, \lambda_{i2}, \dots, \lambda_{ik}, \mu_{i1}, \mu_{i2}, \dots, \mu_{ik})$ ($i = 1, 2, \dots, n$), it means need to meet:

$$M = E(y_i - \bar{y})^2 = E(y_i - a - b_1\lambda_{i1} - b_2\lambda_{i2} - \dots - b_k\lambda_{ik} - c_1\mu_{i1} - c_2\mu_{i2} - \dots - c_k\mu_{ik})^2 = \min \quad (3)$$

Calculate partial derivatives of unknown parameters from the above formula, and make them to be zero, we can obtain the following criteria equations:

$$\begin{aligned} E\bar{y}_i &= na + b_1E\lambda_{i1} + b_2E\lambda_{i2} + \dots + b_kE\lambda_{ik} + c_1E\mu_{i1} + c_2E\mu_{i2} + \dots + c_kE\mu_{ik} \\ E\lambda_{i1}\bar{y}_i &= aE\lambda_{i1} + b_1E\lambda_{i1}^2 + b_2E\lambda_{i1}\lambda_{i2} + \dots + b_kE\lambda_{i1}\lambda_{ik} + c_1E\lambda_{i1}\mu_{i1} + c_2E\lambda_{i1}\mu_{i2} + \dots + c_kE\lambda_{i1}\mu_{ik} \\ E\lambda_{i2}\bar{y}_i &= aE\lambda_{i2} + b_1E\lambda_{i1}\lambda_{i2} + b_2E\lambda_{i2}^2 + \dots + b_kE\lambda_{i2}\lambda_{ik} + c_1E\lambda_{i2}\mu_{i1} + c_2E\lambda_{i2}\mu_{i2} + \dots + c_kE\lambda_{i2}\mu_{ik} \\ &\dots \dots \dots \\ E\lambda_{ik}\bar{y}_i &= aE\lambda_{ik} + b_1E\lambda_{i1}\lambda_{ik} + b_2E\lambda_{i2}\lambda_{ik} + \dots + b_kE\lambda_{ik}^2 + c_1E\lambda_{ik}\mu_{i1} + c_2E\lambda_{ik}\mu_{i2} + \dots + c_kE\lambda_{ik}\mu_{ik} \\ E\mu_{i1}\bar{y}_i &= aE\mu_{i1} + b_1E\lambda_{i1}\mu_{i1} + b_2E\lambda_{i2}\mu_{i1} + \dots + b_kE\lambda_{ik}\mu_{i1} + c_1E\mu_{i1}^2 + c_2E\mu_{i1}\mu_{i2} + \dots + c_kE\mu_{i1}\mu_{ik} \\ E\mu_{i2}\bar{y}_i &= aE\mu_{i2} + b_1E\lambda_{i1}\mu_{i2} + b_2E\lambda_{i2}\mu_{i2} + \dots + b_kE\lambda_{ik}\mu_{i2} + c_1E\mu_{i1}\mu_{i2} + c_2E\mu_{i2}^2 + \dots + c_kE\mu_{i2}\mu_{ik} \\ &\dots \dots \dots \\ E\mu_{ik}\bar{y}_i &= aE\mu_{ik} + b_1E\lambda_{i1}\mu_{ik} + b_2E\lambda_{i2}\mu_{ik} + \dots + b_kE\lambda_{ik}\mu_{ik} + c_1E\mu_{i1}\mu_{ik} + c_2E\mu_{i2}\mu_{ik} + \dots + c_kE\mu_{ik}^2 \end{aligned} \quad (4)$$

Use sample data solve the above $2k+1$ linear equations, obtain the estimated value of undetermined coefficients $a, b_1, b_2, \dots, b_k, c_1, c_2, \dots, c_k$. If the results meet the test of significance, we can get the regression equation. In order to analyze which are the main factors, we can exclude non-significant factors by stepwise regression method. The specific steps are as follows: First do simple regression to each explained variable under consideration with the dependent variable, find explanatory variables which have the largest contribution to the explained variable based on regression equation corresponding, introduce the rest of the explanatory variables gradually. After stepwise regression, make the explanatory variables retain in the model to be both important and have no serious multicollinearity. After solving a new regression equation, solve partial derivative of independent variable in the new regression equation.

$$\begin{aligned} \frac{\partial Y}{\partial \lambda_i} &= b_i \\ \frac{\partial Y}{\partial \mu_i} &= c_i \end{aligned} \quad (5)$$

Values of the partial derivative are the influence extent of variation of λ_i and μ_i on output rate. Suppose the influence extent of λ_i and μ_i while improving maintenance level are the same, in preventive maintenance strategy, while enhancing maintainability, time between failures will be improved, time to repair will be reduced, so λ_i reduced, μ_i increased. make:

$$p_i = |b_i| + |c_i| \quad (6)$$

If we exclude the failure rate and repair rate of a machine in the regression model, it can be considered as a general machine. According to p_i , we can find important equipment and minor equipment considering the failure and repair rate. According to the actual situation of production line, carry Status Maintenance or Preventive Maintenance on important equipment, routine maintenance and inspection on minor equipment, Breakdown Maintenance on general equipment.

4. Numerical Example

4.1 Identify Important Equipment

Suppose a serial production line has four machines, related parameters of each machine are shown in Table 1, try to determine importance rating of four machines.

	processing time T_i (min)	buffer	MTBF (min)	MTTR (min)
Machine1	3	—	730	180
Machine 2	3	15	730	180
Machine 3	3	15	330	230
Machine 4	3	15	930	160

Table 1. Parameters for a serial production line

In the case $s=8$, take 27 levels of failure rates and repair rates uniformly in the vicinity of the known level, factor level table is shown as follows:

No.	factor	level (min)								
		1	2	3	4	...	25	26	27	
1	MTBF ₁	600	610	620	630	...	840	850	860	
2	MTTR ₁	50	60	70	80	...	290	300	310	
3	MTBF ₂	600	610	620	630	...	840	850	860	
4	MTTR ₂	50	60	70	80	...	290	300	310	
5	MTBF ₃	200	210	220	230	...	440	450	460	
6	MTTR ₃	100	110	120	130	...	340	350	360	
7	MTBF ₄	800	810	820	830	...	1040	1050	1060	
8	MTTR ₄	30	40	50	60	...	270	280	290	

Table 2. Factor level table

We can obtain the following experimental scheme according to uniform design table. x_1, x_2, \dots, x_8 mean factors in table 2, N_1, N_2, \dots, N_{27} mean test program of each experiment.

According to the above experimental programs, build production line model and enter the relevant data in Plant simulation software, obtain production rate on each experimental program.

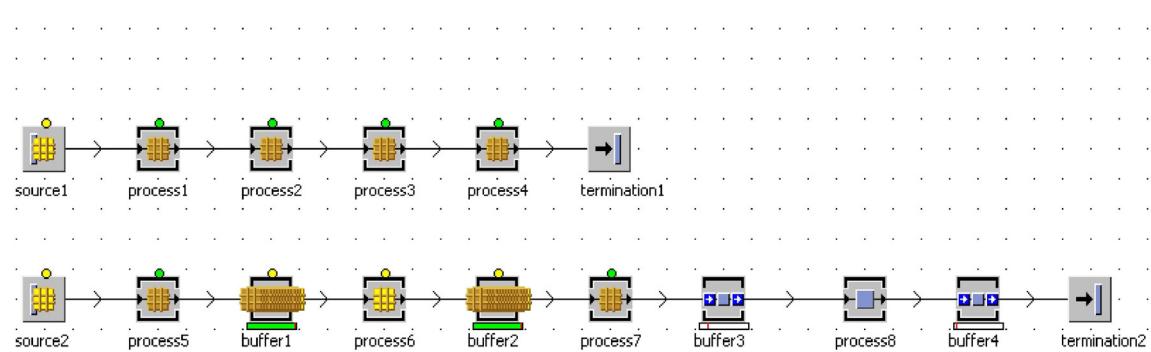


Figure 2. Simulation model of production line

	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8		x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8
N_1	650	60	740	260	270	340	870	120	N_{15}	760	140	660	300	420	210	1050	90
N_2	780	190	860	130	240	320	990	130	N_{16}	770	260	630	90	260	30	860	160
N_3	740	240	710	70	360	330	1040	260	N_{17}	840	200	820	230	450	260	840	170
N_4	700	220	610	240	250	180	960	280	N_{18}	610	300	800	110	410	220	900	240
N_5	670	250	830	270	350	290	970	40	N_{19}	830	70	730	60	400	140	980	190
N_6	600	80	620	210	330	270	1020	150	N_{20}	850	310	750	170	300	190	1030	70
N_7	680	100	640	160	430	310	850	220	N_{21}	810	170	600	140	370	230	810	50
N_8	860	130	690	120	290	280	890	270	N_{22}	750	50	850	190	380	200	940	290
N_9	820	290	650	290	320	350	920	180	N_{23}	720	280	760	200	220	300	800	210
N_{10}	710	150	770	100	440	360	950	60	N_{24}	730	90	700	770	230	120	910	30
N_{11}	620	180	720	310	340	150	820	250	N_{25}	690	120	840	80	310	170	830	100
N_{12}	790	230	780	250	390	100	880	110	N_{26}	800	110	790	280	210	240	1010	230
N_{13}	640	160	810	150	280	110	1060	200	N_{27}	630	210	670	50	200	250	930	80
N_{14}	660	270	680	180	460	160	1000	140									

Table 3. Test program under $U_8(8^{27})$ uniform design

Throughput	Production										rate
	N_1	729	0.438	N_8	876	0.527	N_{15}	1056	0.635	N_{22}	1076
N_2	695	0.418	N_9	792	0.476	N_{16}	1061	0.638	N_{23}	685	0.412
N_3	855	0.514	N_{10}	868	0.522	N_{17}	994	0.598	N_{24}	818	0.492
N_4	961	0.578	N_{11}	1104	0.664	N_{18}	1054	0.634	N_{25}	1074	0.646
N_5	921	0.554	N_{12}	1225	0.737	N_{19}	1241	0.746	N_{26}	796	0.479
N_6	934	0.562	N_{13}	1178	0.708	N_{20}	1014	0.610	N_{27}	757	0.455
N_7	974	0.586	N_{14}	1127	0.678	N_{21}	1035	0.622	Non-fault	1663	-

Table 4. The simulation results

Throughput in Table 4 means yields in simulation time, the first production line in Figure 2 represents ideally production line without fault, production rate is the ratio of throughput in ideally production line and yields in each set of experiments. Multiple linear regression analysis accord with the significant test, the regression equation is:

$$Y = 0.8987 + 40.5215\lambda_1 + 1.1050\lambda_2 - 54.2250\lambda_3 + 0.6859\lambda_4 - 76.3916\mu_1 + 7.7502\mu_2 - 99.6492\mu_3 - 0.8711\mu_4$$

Exclude unrelated variables by stepwise regression analysis, the result is shown in Chart2. We can know that λ_3 and μ_3 are important factors, new regression equation is:

$$Y = 0.7811 - 76.6111\lambda_3 + 7.1261\mu_3$$

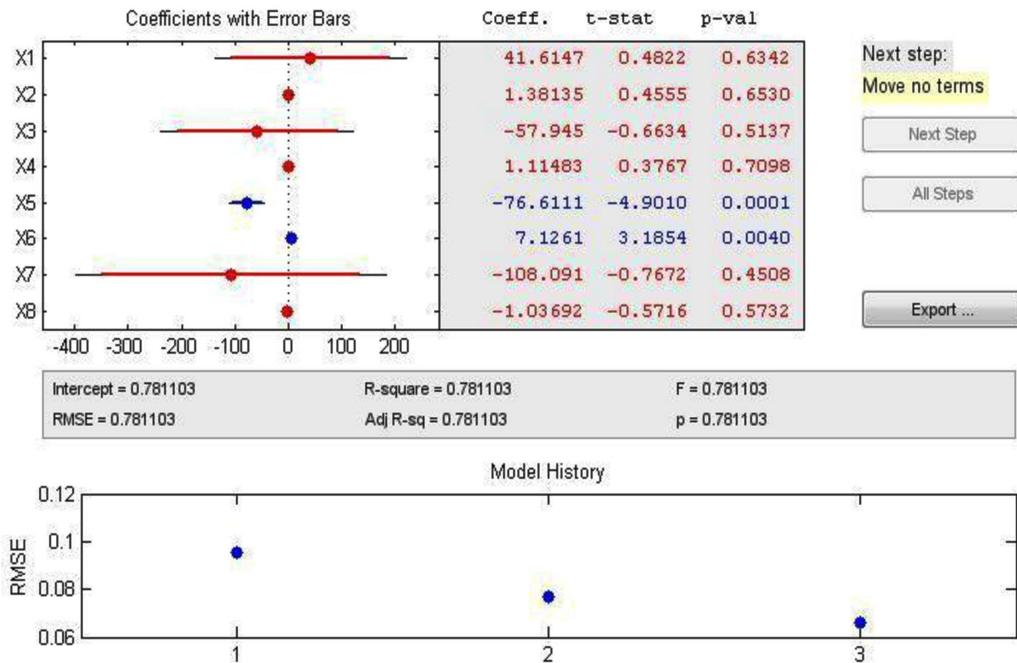


Figure 3. Stepwise regression analysis results

4.2 Model Validation

Machine 3 is important equipment according to Equation 6, the excluded machines 1, 2, 4 can be considered as general equipment. In order to verify the credibility of the proposed method in this paper, we use Bottleneck Identification in PSE Toolbox software[11] find the bottleneck equipment in production line, as shown in figure 4. The figure shows the status of each machine and their buffer, p is productivity, ST is hunger rate for the machines, WIP is the average number of products in each buffer, where the device indicated by the dotted line is bottleneck equipment. This result is the same with important equipment we filter out in the paper, the method used herein may be considered with a certain rationality.

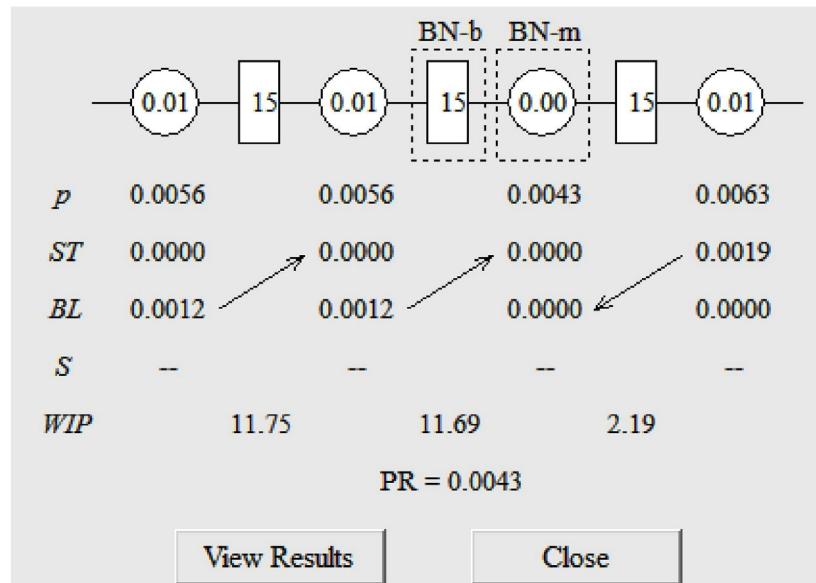


Figure 4. Bottleneck equipment determined by PSE Toolbox software

5. Conclusion

In this paper, we proposed method for determining important equipment based on simulation of the actual automatic production line, the main conclusions are as follows:

(1) Proposed a method for determining important grade for equipment in production line. Determined test program according to uniform design method, and then filtered out the main factors by stepwise regression, determined the important equipment in production line, and used PSE Toolbox model verify the result, got consistent results.

(2) Plant Simulation software can simulate the whole process of a rough pieces enter the production line system, production rate got by the software is more true and accurate. Moreover, if we take yield and other indices as basis to choose important equipment, this method can also be utilized.

Because of the time and data limitations, we suppose the influence extent of λ_i and μ_i while improving maintenance level are the same, so that we can choose important equipment by the result of partial derivatives of the regression equation that plus together. The next step we need collect data of failure rate and repair rate after carry on the corresponding maintenance strategy, study the degree of change, give different weight values to make the results more accurate.

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