Research of Multi-target Shop Schedule based on Particle Swarm and Grey Relation

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***Abstract*—In order to improve efficiency of the workshop, a new scheduling method is put forward by coupling polychromatic theory, particle swarm algorithm and grey correlation theory. Firstly, considering manufacturing resources allocation problem, manufacturing resource description and reasoning is realized by polychromatic set theory to satisfy manufacturing process requirement. Secondly, manufacturing resources selection evaluation system is constructed, and manufacturing resources multi-objective selection problem is resolved by grey correlation theory and analytic hierarchy process. Lastly, on the basis of manufacturing resources selection, Job shop scheduling problem for minimizing span optimization objective is solved by the particle swarm algorithm. The method is validated the effectiveness of shop scheduling by an example, which is coupling polychromatic particle swarm and grey relation theory.**

Keywords-Shop Scheduling; Polychromatic Theory; Particle Swarm Algorithm; Grey Correlation

I. INTRODUCTION

As implement department of production, workshop feeds back large amounts of real-time manufacturing data, and it needs plan information from the upstream sector in time. It's very important to manage, control and dispatch manufacturing resource for manufacturing enterprise. Job Shop Scheduling Problem (JSP) is also the core function module of Manufacturing Execution System (MES). Relevant literature mostly chooses classic JSP as research subject, and focuses on optimize algorithms, management mode and so on. In this paper, relations of discrete manufacturing feature, schedule policy and evaluation index are analyzed, and multi-objective evaluation system and computation method for JSP are constructed. Meanwhile, manufacturing resource optimal allocation is realized by polychromatic set theory, and job shop scheduling problem is resolved based on particle swarm optimization algorithm. Lastly, the hierarchical analysis method and grey correlation theory are used to realize the multi objective JSP.

II. PRE-ELECTION MANUFACTURING RESOURCES POLYCHROMATIC ALLOCATION

Actual workshop scheduling problem is complicated, and it needs to consider satisfying various constraints, including processing equipment efficient allocation. Polychromatic set is the hierarchical information system, and it can organize, analyze and compute relevant information at all levels of the system.

$MS=(B, FF(b), FF(B), [A\times FF(b)], [A\times FF(B)], [B\times B(FF)])$

B=(b1,…,bi,…,bn) is a set constructed by all elements, and FF(B)=(FF1,…, FF2,…, FFm) represents general color. FF(b) indicates each element color in MS. FFj(bi) shows relationship of element bi and general color FFj property, i=1,2,…,n, j=1,2,…,m. B×FF(b) is individual color of all elements in polychromatic set, and B×FF(B) represents relationship of general property and individual property in polychromatic set. B×B (FF) indicates all individual element construction set with whole general color.

Vertex and edge in the polychromatic diagram can be colored to describe more relation and feature of the real system. The diagram is defined as following:

$MG=(FF(G), MSB, MSC)$

$MSB=(A,FF(b),FF(B),[A\times FF(b)],[A\times FF(B)],[B\times B(FF)]$

$MSC=(C,FF(c),FF(C),[C\times FF(c)],[C\times FF(C)],[C\times C(FF)]$

FF(G)，FF(B) and FF(C) respectively represent entirety color, vertex color and edge color. B×FF(B) is contour boolean matrix to color vertex, and C×BF(C) indicates the contour matrix to color edge.

In terms of part feature and processing requirement, it is necessary to arrange appropriate manufacturing resources. Mathematical model of manufacturing resources allocation consists of processing system contour matrix [M×FF(M)] and relation graph of element. FF(M)={ FFi|i∈N} represents manufacturing system entirety color or contour, and contour Boolean logical vector FF(ui)= { FFij| FFij ∈(0,1)} is used to determine whether the resource has the specified process capability.

III. GREY CORRELATION SELECTION OF PROCESSING EQUIPMENT

During the practical production, a wide-range processing equipment is available for manufacturing task. The issue, how to select optimum equipments from processing time, machining cost, processing quality and machine reliability, will have to be faced in the workshop dispatch.

1) Time index (L1)

Time index includes processing time (L_{11}) and cool down time (L_{12}), and the indexes value can't be big enough.

2) Cost index (L2)

Cost index consists of machining cost (L_{21}), maintenance cost (L_{22}) and equipment depreciation cost (L23). The indexes value can't be small enough.

3) Quality index (L3)

Quality index includes dimensional accuracy (L_{31}), surface roughness (L_{32}) and shape precision (L_{33}). According to production specific technical requirement, there are appropriate equipments as the candidate by its machining quality.

4) Reliability index (L4)

Reliability index includes equipment loading rate (L_{41}), equipment failure rate (L_{42}) and equipment installation rate (L_{43}). Index L_{41} and L_{43} value can't be big enough, and Index L_{42} value can't be small enough.

(5) Green character index (L_5)

Green character index is made up of energy consumption (L_{51}) and noise pollution (L_{52}), and the value of L_{51} and L_{52} can't be small enough.

Qualitative and quantitative indexes of the evaluation system can be normalized. Cost indexes and efficiency indexes are respectively disposed in terms of equation (1) and equation (2).

$$\bar{\delta}_{ij} = \left[\delta_{ij} \left(\sum_{k=1}^{m} \delta_{kj}^{-1} \right) \right]^{-1} \tag{1}$$

$$\bar{\delta}_{ij} = \delta_{ij} \Big/ \sum_{k=1}^{n} \delta_{kj} \tag{2}$$

Grey correlation degree is used to judge closeness of alternative and object scheme, and the greater the grey correlation degree, the better the scheme is. Grey correlation is described as below:

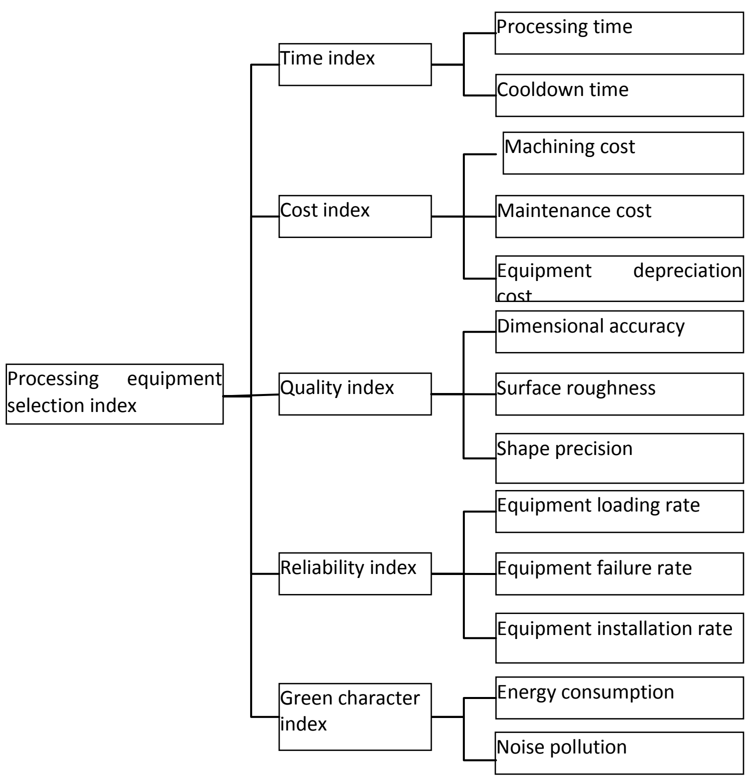

Figure 1. Processing equipment selection evaluation index system

Standard reference sequences is $X_0=\{X_0^{(1)}, X_0^{(2)}, X_0^{(3)}, \ldots, X_0^{(n)}\}$, and Sequences to be compared are $X_j=\{X_j^{(1)}, X_j^{(2)}, X_j^{(3)}, \ldots, X_j^{(n)}\}$, $j\in[1,\ldots,m]$. Grey correlation coefficients of each scheme are calculated by equation (3) and equation (4).

$$\xi_i^{(k)} = \frac{\Delta \min + \sigma \Delta \max}{\Delta ik + \sigma \Delta \max} \tag{3}$$

$$\Omega_{m\times n} = \begin{bmatrix} \zeta_1^{(1)}, \zeta_1^{(2)}, \cdots, \zeta_1^{(n)} \\ \zeta_i^{(1|)}, \zeta_i^{(2)}, \cdots, \zeta_i^{(n)} \\ \zeta_m^{(1)}, \zeta_m^{(2)}, \cdots, \zeta_m^{(n)} \end{bmatrix} \tag{4}$$

$$\Delta \min = \min_i \min_k \left| X_i^{(k)} - X_0^{(k)} \right| \tag{5}$$

$$\Delta \max = \max_i \max_k \left| X_i^{(k)} - X_0^{(k)} \right| \tag{6}$$

$$\Delta ik = \left| X_i^{(k)} - X_0^{(k)} \right| \ , \ i \in \{1, \cdots, m\} \tag{7}$$

IV. JOB SHOP SCHEDULING METHOD BASED ON THE PARTICLE SWARM ALGORITHM

In order to manufacture all products as early as possible, model objective function is product make span, and mathematical model of JSP is described as following:

$$\begin{aligned} &\min \max_i^n C_i = \min \max_i^n \left(S_i + T_i \right) \\ &s.t. \ T_{i(k-1)} - \left(S_{ik} - S_{i(k-1)} \right) \le 0 \qquad 1 \le i \le n, 2 \le k \le m \\ &\quad -S_{i1} \le 0 \\ &\quad S_{ikp} + T_{ik} - S_{jhp} \le 0 \ or \ T_{jh} + S_{jhp} - S_{ikp} \le 0 \end{aligned} \tag{8}$$

Constraint 1 indicates whether the workpiece can be processed in a certain procedure. Constraint 3 shows that each equipment can only dispose one procedure of a workpiece at the same time.

Particle swarm optimization algorithm (PSO) is proposed to mimic the foraging behavior of birds. Namely, the solution of the optimization problem is obtained by the competition and cooperation relationship of every individual. So it has the ability to remember the current best position of the particle itself and the best position of the swarm. We are working on the assumption that population size of particle swarm is n, and optimization solution is searched in d dimension space.

*PX*i=[*px*i,1,*px*i,2, …,*px*i,d] is position information of particle *i*.

*PV*i=[*pv*i,1,*pv*i,2, …,*pv*i,d] indicates speed information of particle *i*.

*P*i=[*pp*i,1, *pp*i,2, …, *pp*i,d] represents best position of particle *i* to pass.

*P*g=[*pp*g,1, *pp*g,2, …, *pp*g,d] indeicates the optimal iterative position of the particle swarm.

Particle speed and position information can be updated by equation (9) and equation (10).

pvi,j(t+1)= pwvi,j(t)+ pc1r1[pi,j(t)- pxi,j(t)]+c2r2[ppg,j(t)- pxi,j(t)] (9)

pxi,j(t+1)= pxi,j(t)+ pvi,j(t+1) j=1,2...,d (10)

In order to balance the particle searching ability, the parameter pw is set as the inertia weight factor. c_1 and c_2 are both non negative constants, which are used to adjust the learning ability of particles. r_1 and r_2 are random numbers of uniform distribution, and their interval is 0 and 1. In addition, in order to restrain the particle's range of motion, the velocity and position of the particle are added to the interval $[v_{min}, v_{max}]$ and $[x_{min}, x_{max}]$. According to JSP model, the solving process of the PSO is shown as follows:

Step1：On the basis of workpiece process of the encoding way, the parameters are initialized.

a) The number of particles n, maximum iterations bird-set, space dimension dim, acceleration constant c1 and c2 and inertia weight factor w are set.

b) For JSP with n workpieces, q process for each workpiece and m machine, speed and position of each particle in swarm are randomly initialized, and initialization character string length is n× q.

Step2：Each particle is evaluated.

a) Current target value of each particle current position is put into the corresponding vector pbest.

b) Best value is selected from pbest, and put into the variable gbest.

Step3：Speed and position information of each particle are updated by equation (9) and (10).

Step4：All particles in swarm are evaluated again, after they were updated.

a) Current target value of each particle and corresponding value stored in pbest are compared.

b) If current target value is more excellent, then the current target value is set as new pbest target value.

c) Otherwise, the original pbest target value is maintained unchanged.

Step5：It is determined whether to meet the conditions of convergence.

a) If it reaches maximum iterations bird-set, then result is output.

b) Otherwise, it jumps to Step3, and continues to cycle.

V. CASE STUDY

In the manufacturing system, there are 6 workpieces and 30 available selection machines, and there are 6 machining processes for each workpiece. In processing system contour Boolean matrix, FF_1-FF_6 indicates the process, and FF_7-FF_9 represents the manufacturing material. Besides, M_1-M_6 indicates the processing type, M_7-M_{12} represents the equipment type, and M_{13}-M_{15} denotes the fixture type. The process contour of part is $FF(A)=(FF_1,FF_2,FF_6,FF_9)$, and manufacturing system general contour is $FF(M)=(FF_1, FF_2,FF_3,FF_4,FF_5, FF_6,FF_7,FF_8,FF_9)$. Machining path can be acquired by reasoning of correlation matrix $[M\times FF(M)]$, and vertical element to satisfy certain condition is derived from matrix horizontal item. If the equipment has the process ability, the element is indicated as the symbol ●. Otherwise, the element is represented as the symbol ○ in TABLE 1.

For equipment M_3, the contour description is shown as following to determine whether M_3 has specified process ability. $FF(M_3) = (1,1,0,1,0,0,1,0,1)$

Product to be processed initial and finial condition respectively is:

TABLE I. EQUIPMENT PROCESS CONTOUR MATRIX

	F1	F2	F3	F4	F5	F6	F7	F8	F9
M1	○			●			●		
M 2		●	●			○		●	●
M 3	●	○		●			●		●
M 4	●				○			●	
M 5			○	●		●			●
M 6		●		●		●		○	
M 7	●		●		●		○		●
M 8	●	●	●						○
M 9					●	●			
M 10		●	●	○				●	
M 11	○		●		●				
M 12				●	●	○			
M 13		○	●	●				●	
M 14				●	○		●		●
M 15		●	○				●		

FF (A) = (1,1,0,0,0,1,1,0,0,1)

$FF(A)0 = (0,0,0,0,0,0,0,0,0,1)$

Product contour composition is calculated, and M_3 is judged whether meet process requirement:

$FF(A)^{I}_{11}=\overline{FF}(A)0 \wedge FF(M_3) \wedge FF(A)= (1,1,1,1,1,1,1,1,0) \wedge (1,1,0,1,0,0,1,0,1) \wedge (1,1,0,0,0,1,1,0,0,1) = (1,1,0,0,0,0,1,0,0,1)$

Parts contour that can not be processed by production equipment M_3 is calculated:

$FF(A)^{II}_{11}= \overline{FF}(A)0 \wedge \overline{FF}(M_3) \wedge FF(A)= (1,1,1,1,1,1,1,1,0) \wedge (0,0,1,0,1,1,0,1,0) \wedge (1,1,0,0,0,1,1,0,0,1) = (0,0,0,0,0,1,1,0,0,0)$

According to the calculation result, equipment M3 can not meet to requirement process 6 and 7. In terms of above calculation method, manufacturing equipment allocation is realization to select appropriate machine set for each part process.

By Delphi survey of the manufacturing enterprise, priority order of evaluation indexes at all levels is: $L_1 > L_2 > L_4 > L_6 > L_3 > L_5$, $L_{11} > L_{12}$, $L_{21} > L_{22} > L_{23} > L_{24}$, $L_{33} > L_{32} > L_{31} > L_{34}$, $L_{41} > L_{42} > L_{43}$, $L_{51} > L_{52}$. Judgment matrixes at all levels are respectively constructed according to AHP scale method.

$$D=\begin{bmatrix} 1 & 2 & 3 & 4 & 5 \\ 1/2 & 1 & 2 & 3 & 4 \\ 1/3 & 1/2 & 1 & 2 & 3 \\ 1/4 & 1/3 & 1/2 & 1 & 2 \\ 1/5 & 1/4 & 1/3 & 1/2 & 1 \end{bmatrix} \quad D_1=\begin{bmatrix} 1 & 3 \\ 1/3 & 1 \end{bmatrix} \quad D_2=\begin{bmatrix} 1 & 2 & 3 & 4 \\ 1/2 & 1 & 2 & 3 \\ 1/3 & 1/2 & 1 & 2 \\ 1/4 & 1/3 & 1/2 & 1 \end{bmatrix}$$

$$D_3=\begin{bmatrix} 1 & 1/2 & 1/2 & 3 \\ 2 & 1 & 1/2 & 4 \\ 2 & 2 & 1 & 5 \\ 1/3 & 1/4 & 1/5 & 1 \end{bmatrix} \quad D_4=\begin{bmatrix} 1 & 1/2 & 3 \\ 2 & 1 & 3 \\ 1/3 & 1/3 & 1 \end{bmatrix} \quad D_5=\begin{bmatrix} 1 & 3 \\ 1/3 & 1 \end{bmatrix}$$

According to equation $AW=\lambda_{\max}W$, comprehensive weight vector of all indexes is calculated W=[0.273 0.068 0.127 0.075 0.044 0.026 0.003 0.052 0.077 0.013 0.057 0.031 0.017 0.042 0.015]^T. Taking the first process of workpiece 1 for instance, there are 8 machines can be selected, and the quantitative results of various indexes are shown in TABLE 2.

Reference sequence X0 and difference sequence matrix θ of evaluation case are determined to finish evaluation index data preprocessing.

$$\theta=\begin{bmatrix} 0.00 & 0.00 & 0.03 & 0.01 & 0.01 & 0.07 & 0.00 & 0.07 & 0.01 & 0.01 & 0.00 & 0.00 & 0.02 & 0.00 & 0.03 \\ 0.03 & 0.08 & 0.04 & 0.00 & 0.02 & 0.11 & 0.01 & 0.08 & 0.02 & 0.00 & 0.02 & 0.03 & 0.01 & 0.03 & 0.00 \\ 0.03 & 0.03 & 0.00 & 0.01 & 0.03 & 0.10 & 0.02 & 0.01 & 0.03 & 0.00 & 0.02 & 0.13 & 0.01 & 0.03 & 0.03 \\ 0.00 & 0.04 & 0.07 & 0.01 & 0.00 & 0.07 & 0.01 & 0.02 & 0.00 & 0.01 & 0.02 & 0.07 & 0.00 & 0.03 & 0.05 \\ 0.06 & 0.13 & 0.08 & 0.10 & 0.02 & 0.05 & 0.00 & 0.08 & 0.00 & 0.00 & 0.01 & 0.23 & 0.02 & 0.06 & 0.04 \\ 0.03 & 0.11 & 0.03 & 0.07 & 0.02 & 0.02 & 0.02 & 0.03 & 0.04 & 0.00 & 0.02 & 0.20 & 0.02 & 0.00 & 0.02 \\ 0.06 & 0.09 & 0.01 & 0.05 & 0.00 & 0.00 & 0.01 & 0.00 & 0.01 & 0.00 & 0.02 & 0.07 & 0.03 & 0.03 & 0.01 \\ 0.09 & 0.12 & 0.06 & 0.02 & 0.03 & 0.01 & 0.02 & 0.07 & 0.00 & 0.00 & 0.01 & 0.03 & 0.01 & 0.06 & 0.03 \end{bmatrix}$$

According to difference sequence matrix θ, parameters are calculated min(θ)=0, max(θ)=0.914. Let resolution coefficient σ=0.3, and grey correlation coefficient matrix is resolved by equation 3.

$$\xi=\begin{bmatrix} 1.00 & 1.00 & 0.47 & 0.83 & 0.54 & 0.31 & 0.66 & 0.25 & 0.56 & 0.23 & 1.00 & 1.00 & 0.28 & 1.00 & 0.38 \\ 0.47 & 0.33 & 0.38 & 1.00 & 0.37 & 0.23 & 0.33 & 0.23 & 0.38 & 0.33 & 0.32 & 0.67 & 0.52 & 0.38 & 1.00 \\ 0.47 & 0.60 & 1.00 & 0.67 & 0.23 & 0.25 & 0.28 & 0.71 & 0.29 & 0.33 & 0.32 & 0.35 & 0.52 & 0.35 & 0.38 \\ 1.00 & 0.47 & 0.27 & 0.76 & 1.00 & 0.31 & 0.43 & 0.62 & 1.00 & 0.23 & 0.32 & 0.51 & 1.00 & 0.38 & 0.23 \\ 0.31 & 0.23 & 0.23 & 0.23 & 0.28 & 0.40 & 1.00 & 0.24 & 1.00 & 1.00 & 0.50 & 0.23 & 0.37 & 0.23 & 0.27 \\ 0.47 & 0.26 & 0.47 & 0.30 & 0.37 & 0.57 & 0.28 & 0.49 & 0.23 & 1.00 & 0.23 & 0.26 & 0.37 & 1.00 & 0.43 \\ 0.31 & 0.31 & 0.64 & 0.35 & 1.00 & 1.00 & 0.33 & 1.00 & 0.56 & 0.33 & 0.23 & 0.51 & 0.23 & 0.38 & 0.60 \\ 0.23 & 0.24 & 0.31 & 0.55 & 0.23 & 0.73 & 0.23 & 0.26 & 1.00 & 0.23 & 0.50 & 0.67 & 0.52 & 0.23 & 0.33 \end{bmatrix}$$

In terms of grey correlation coefficient weight sum method, correlation degree of the evaluation scheme is calculated $R=(r_1, r_2, r_3, r_4, r_5, r_6, r_7, r_8)$= (0.697,0.420,0.555,0.633,0.316,0.390,0.442,0.355). The ranking result of 8 machines to be evaluated can be acquired $M_1>M_4>M_3>M_7>M_2>M_6>M_8>M_5$. It is inescapably clear that the first equipment to be selected for first process of workpiece 1 is M_1. Appropriate equipments for every process of all equipment are also acquired in terms of above iterative calculation.

The PSO is applied to optimize the machining sequence of the workpiece on each machine, and the algorithm resolved procedure has been introduced in section 4. The optimal production scheduling scheme is [4, 6, 4, 5, 4, 5, 4, 6, 4, 1, 2, 1, 1, 5, 6, 2, 2, 5, 3, 3, 5, 6, 4, 1, 5, 2, 1, 1, 2, 3, 5, 1, 6, 4, 3, 1, 3, 3, 6, 5, 3, 2, 4, 2, 2, 6, 6, 3]. The maximum makespan of the scheme is 65 hours, and each machine makespan respectively is (36h, 64h, 58h, 51h, 50h, 65h, 63h, 59h). The dispatch result is shown as Figure 2.

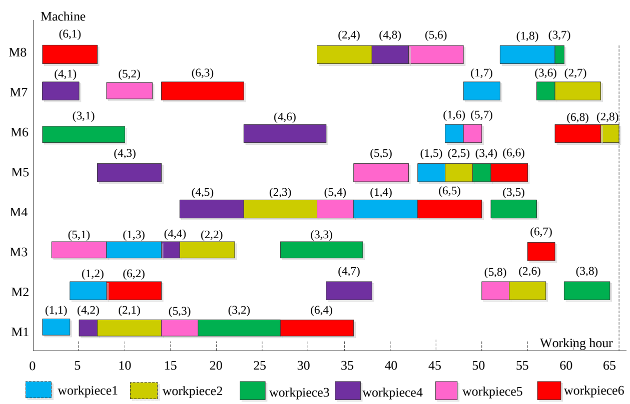

Figure 2. Job shop multi objective dispatch Gantt diagram

VI. CONCLUSIONS

In order to optimize production, polychromatic theory is applied in manufacturing resource allocation for JSP. Based on mathematical modeling and analysis, selection evaluation system of manufacturing resource is constructed, and the selection method is put forward by the AHP method and grey correlation theory. Lastly, the PSO for minimal makespan is used to solve JSP. The method is a feasible solution by an illustration, and it can be used to resolve the multi-objective JSP.

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TABLE II. EVALUATION INDEX AND QUANTITATIVE DATA OF AVAILABLE PROCESS EQUIPMENT

	M_1	M_2	M_3	M_4	M_5	M_6	M_7	M_8
Processing time /h	3	4	4	3	5	4	5	6
Cooldown time /min	12	30	18	20	42	38	32	40
Maching cost /(CNY.h^{-1})	40	45	30	55	60	40	35	50
Maintenance cost /CNY	34	34	37	35	65	55	50	40
Storage charge/CNY	15	16	18	14	17	16	14	18
Equipment depreciation cost	1.2	1.5	1.4	1.2	1.0	0.8	0.6	0.7
Dimensional accuracy /μm	33	35	36	34	32	36	35	37
surface roughness /mm	6.1	6.4	3.6	3.8	6.3	4.2	3.2	6.0
shape precision /μm	13	14	15	12	12	16	13	12
Position accuracy /μm	54	53	53	54	52	52	53	54
Equipment loading rate	0.9	0.8	0.8	0.8	0.85	0.75	0.75	0.85
Equipment failure rate	0.01	0.02	0.05	0.03	0.08	0.07	0.03	0.02
Equipment installation rate	0.8	0.9	0.9	0.95	0.85	0.85	0.75	0.9
Energy consumption /J	3	4	5	4	5	3	4	5
Noise pollution /dB	25	20	25	30	28	24	22	26