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Production Process Object Model Research Based on Petri Net Techniques

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1. Introduction

A bottleneck in production process is a link which hindered business process to increase effective output greater or reduce inventory and cost [1]. Solve the bottleneck of the traditional method of production is usually through improved technology, increased scale of production [2], increasing capital investment, etc. to achieve. However, this method is usually the bottleneck occurs in quite a long time before they can be discovered and resolved, often resulting in wasted production capacity.

In recent years, with a variety of simulation techniques become more sophisticated, people started to recognize the use of simulation technology to address bottleneck in business results are quite remarkable [3]. Such as the use of SIMOGRAMS method to determine the production process bottleneck workshop and improve the bottleneck cell [4]; use Em-plant to build production line simulation model and optimize production line configuration and layout [5] [6];the use of WITNESS studied the production efficiency of the system issues to improve the initiative and creativity of workers [7].

To some extent the use of simulation technology can solve production bottleneck problem, but the simulation model building takes longer, is not strong universal and the need of trained professional model talent, so it is not conducive for the production process widely used in various sectors. Through research, the production process conduct the dynamic system model Petri net techniques [8], combined with simulation software, and put forward the production process object model (referred to as PPOM) method.

2. Production Process Object Model (PPOM)

2.1 PPOM thought

PPOM is a production process object model method, which combines object-oriented thought (Object Oriented, OO) and Petri net techniques, make each processing site in the production process, production cell or working procedure to a high degree of abstraction [9],then abstract entity place sub-module, combined with the actual situation of production, optimize the abstract entity place sub-module, establish an PPOM abstract model of production system and form an organic production system, build production capacity analysis objective function model, using simulation annealing algorithm to find out the minimum production cell and detect the bottleneck cell of the production system.

PPOM method not only can analyse the dynamic production capacity of the production process and working procedure,but also has the advantages of modular, object-oriented as well as visually and clear hierarchy, also suitable for model of various processing cells.in each cell, production capacity is estimated that production systems will help to predict the bottleneck in advance, and to improve the processing cell to make a timely manner in order to shorten the production cycle, increase productivity and efficiency of production systems.

As OO thought emphasizes the specific data and operations are encapsulated in black boxes, no need to consider the object's internal operations and state change, but only care about the message exchange through the interface between objects, therefore, putting forward the PPOM Theoretical Basis is feasible.

2.2 PPOM definition

Petri nets can be used to describe the system's complex event logic and sequential relationship graphically, but also can analyse the system based on mathematical methods of quantitative, so in the manufacturing system analysis, model and control, they are widely used [10]. As system complexity increases, the system PN model and analysis become very complicated, due to the lack of modular, reusability and other shortcomings, increases the reconstruction time of PN model.To this end, in the production process model, the introduction of PPOM thought, combined with high-level Petri net (OPN) techniques, putting forward Production process object modeling-Object-oriented Petri nets ($PPOM - OPN$) method.

Application of the concept of OPN, regard the production system as a series of objects and message transmisson between the objects, use CPNs (colored Petri net) describing the object, The CPNs model of the object obtained was called Object-oriented Petri nets (OPN); message transmission between objects was described by network diagram, which was built by transition and directed arc,also called Message Passing Relation nets(MPRN).

Definition 1.1 PPOM Definiton

Seven-tuple is expressed as

$$PPOM - OPN_i = \{SP_i, AT_i; IM_i, OM_i, I_i, O_i, C_i\} \tag{1.1}$$

Thereinto:

1. SP_i —State Place finite set
2. AT_i —Activity transition finite set
3. IM_i —input message place finite set
4. OM_i —output message place finite set
5. $C(SP_i)$ —state place color Collection
6. $C(AT_i)$ —Activity transition color collection
7. $C(IM_i)$ —input message place color collection
8. $C(OM_i)$ —output message place color collection
9. $I_i(P,T)$ —from place P to transition T input mapping function : $C(P) \times C(T) \to N$ (Non-negative integer), Corresponds to the color directed arc from P to T,here $P = SP_i \cup IM_i$, $T = AT_i$, $I(P,T)$ for the matrix.
10. $O_i(P,T)$ —from transition T to the place P output mapping function: $C(T) \times C(P) \to N$ (Non-negative integer), Corresponds to the color directed arc from T to P.here $P = SP_i \cup OM_i$, $T = AT_i$, $O(P,T)$ for the matrix.

$PPOM-OPN_i$ The internal state place and activity transition describes the dynamic properties of OPN object model, that the production process or working procedure bring changes in the internal state of the production cell, while the input message received from other objects (as the previous production cell) of message and through output message place gate on the activities of production cells to the next incoming process or procedure(that is the input message place).

Definition 1.2 Message Passing Relation nets among production cells

In the production process, message Passing Relation nets from message exporter Ob_i to message inporter Ob_j ($i \neq j$) are expressed as:

$$R_{ij} = \left\{OM_i, g_{ij}, IM_i, C(OM_i), C(IM_j), C(g_{ij}), I_{ij}, O_{ij}\right\} \tag{1.2}$$

Thereinto:

1. OM_i —Object Ob_i input message place finite set
2. IM_j —Object Ob_j output message place finite set
3. g_{ij} —from Ob_i to Ob_j message transmission gate finite set
4. $C(OM_i)$ — Ob_i output message place color collection
5. $C(IM_j)$ — Ob_j input message place color collection
6. $C(g_{ij})$ — g_{ij} color collection
7. $I_{ij}(OM_i, g_{ij})$ —from output message place OM_i to the gate g_{ij} input mapping function,it's $C(OM_i) \times C(g_{ij}) \rightarrow N$ (Non-negative integer), corresponds to the color directed arc from OM_i to the g_{ij} .

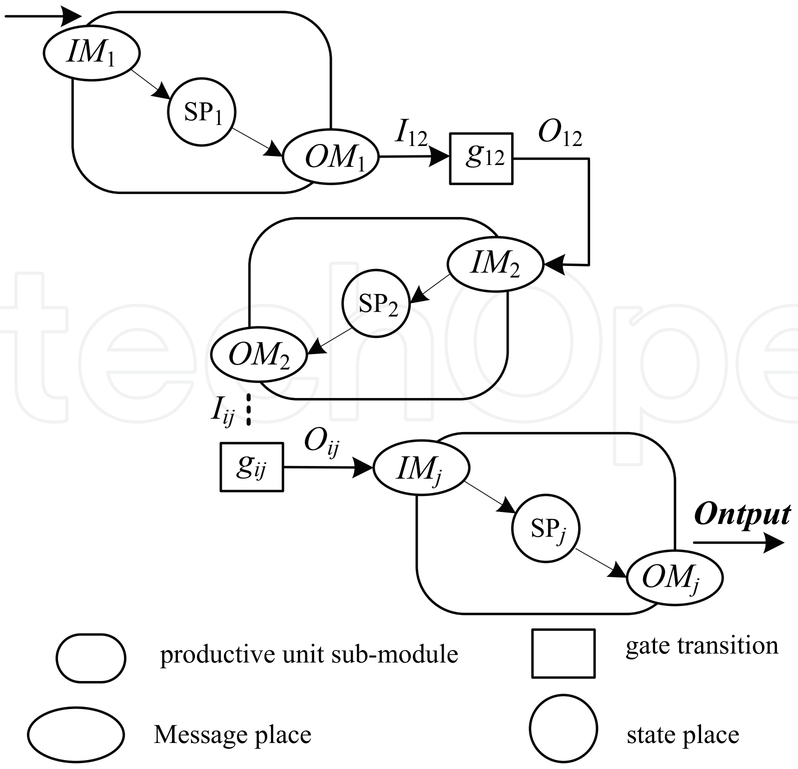

Fig. 1. Relation nets among production cells

8. $O_{ij}(IM_j, g_{ij})$ —The gate g_{ij} to the input message place IM_j output mapping function,it's $C(g_{ij}) \times C(IM_j) \to N$ (Non-negative integer), corresponds to the color directed arc from g_{ij} to OM_i .

Known by definition 1.2, the production sub-module are through input / output mapping functions and message transmission gate to fulfill message transmission and feedback. Message gate is a special transiton in OPN that express message transmission between different OPN "incident", as shown in Figure 1.

3. Bottleneck detection based on PPOM

3.1 Bottleneck detection based on PPOM

PPOM is a dynamic model method of production process, this method not only for the pre-estimation of the bottleneck before products into production, and is also suitable to explore the new bottleneck cell after bottleneck transfer occurred. PPOM bottleneck detection process is as follows:

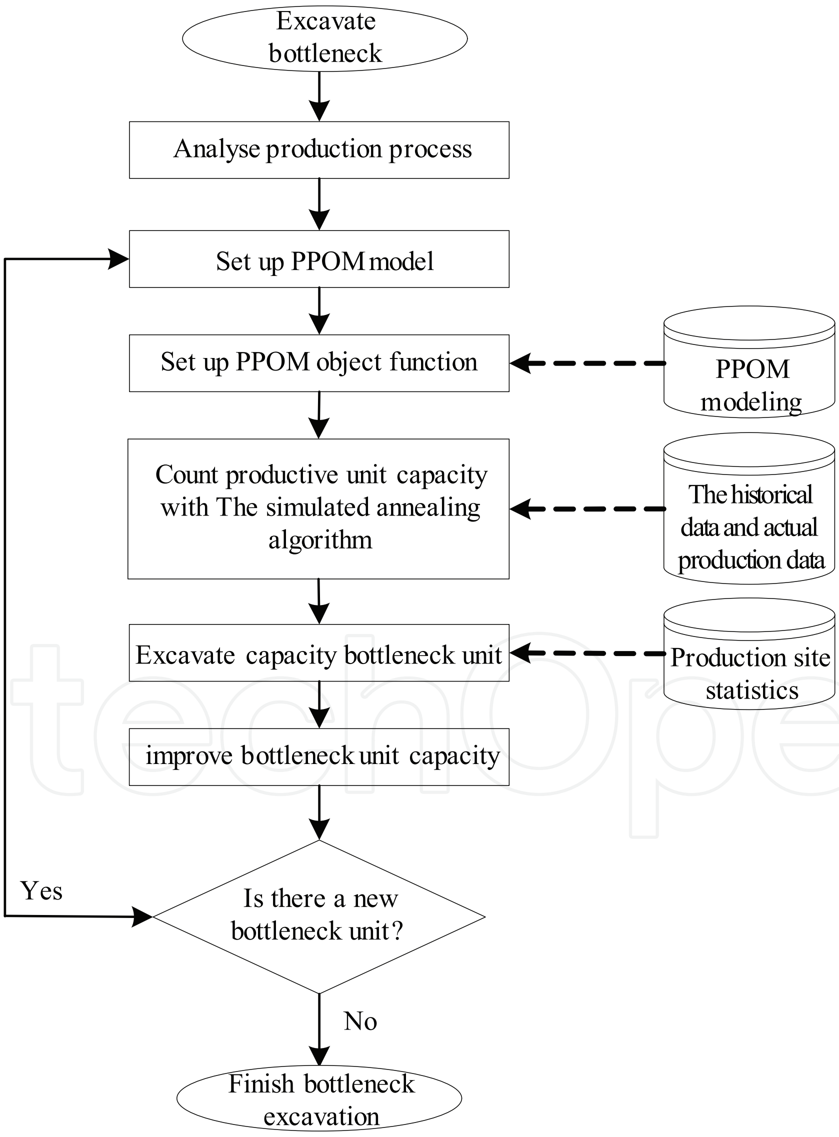

Fig. 2. Bottleneck detecting process based on PPOM

1. PPOM abstract model
2. PPOM objective function model
3. Use simulated annealing algorithm to calculate the production cell capacity
4. Find the minimum production capacity process cell
5. Detect bottleneck production capacity cell
6. Put forward improvement measures accordingly
7. Analyse whether appear new bottleneck in production cells, if it exists, back to Step 2 to re-cycle, otherwise end the bottleneck detection process, specifically shown in Figure 2.

3.2 Abstract model based on PPOM

3.2.1 Abstract model

The production process has the specific entitity object $PPOM-OPN$ on the level of OPN from its inherited class, reflecting the succession of OPN method, that is the object class has its own properties and methods. Therefore, in the build-time of $PPOM-OPN$, not only to examine entity object state place SP and activities transition AT as to establish common PN, but also know all input message place IM and output message place OM of entities.

Use PPOM method, abstract each processing cell in the production process to closed entity place Mi, IMi shows i production cell input message place, OMi shows i production cell output message place after operation, SPi shows i-production cell state place, that is intermediate processing status of production place Mi. Methods using PPOM abstract model shown in Figure 3.

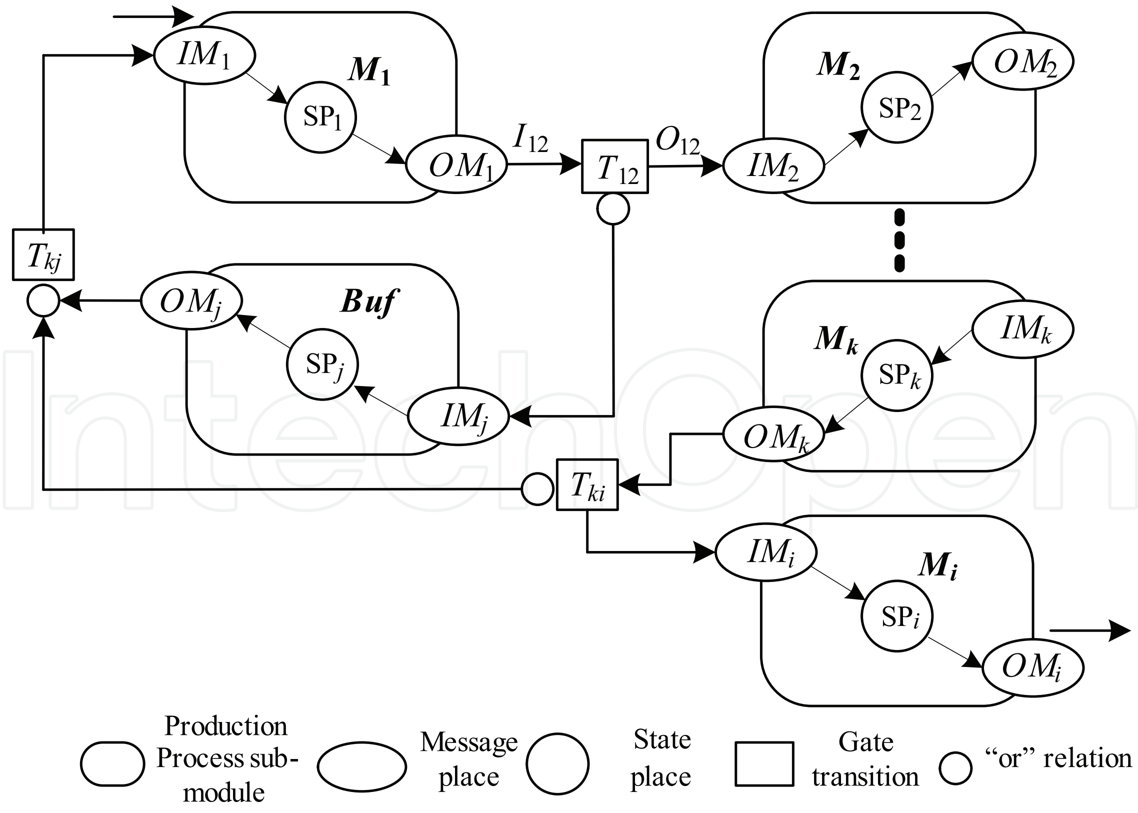

Fig. 3. Abstract model construction based on PPOM

Figure 3 shows the abstract model of the entire production process $PPOM - OPN$, the concrete operation of the various production cells are encapsulated in rounded rectangular frame, each production cell sub-module through input / output mapping functions and message transmission gate to fulfill message transition and feedback. Message gate is a special transiton in OPN that express message transmission between different OPN "incident".

3.2.2 Capacity analysis of abstract model

1. Deadly embrace analysis

Manufacturing system dynamics characteristics can be described by various objects OPN(Obi) of manufacturing system OPN and the relationship between objects (R_{ij}),the various sub-objects can inherit from its parent class property.Therefore,by constructing Object Communication Net(OCN) between object classes, the use of non-variable analysis can be carried out for deadly embrace detection. An analysis of the capability of each object class OCN, also mastered the situation of the whole production system. If an object class OCN exists deadly embrace , there may be message transmission between object classes result. For any sub-module object of abstract model, using the module objects to constructe the corresponding OCN (OCi). Construction of sub-module object class OCN steps:

1. Start from any output message place $om(om \in OM_i)$ of O_i, identify the connected relationship $R_{ij} = (OM_i, g_{ij}, IM_j)$ and defining input message place $im(im \in IM_j)$ corresponding to O_j. Meanwhile, with the state place $sp(sp \in SP_j)$ by using abstract objects $AO_{ij}(sp)$ instead of objects O_j,here sp is decided by input / output relationship $IM_j - AT_j - SP_j$.
2. Through stimulating transition $g(g \in g_{ij})$ immediately connects om and $AO_{ij}(sp)$ of O_i.
3. For the abstract object O_j,from it's definition input / output relationship $SP_j - AT_j - OM_j$ to find output message place $om(om \in OM_j)$;
4. If what 3) found of *om* is equal to the start output message place from O_i, then stop (that is the object OCN has been built). Otherwise, the next step;
5. According to the corresponding mutual connection relationship $R_{jj'}(OM_{j'}, g_{jj'}, IM_{j'})$ $j' = j, j = 1, 2, \cdots, I$,through stimulating transition g immediately to find input message place $im(im \in IM_{j'})$ Corresponding to O_j.meanwhile, with the state place $sp(sp \in SP_j)$ by using abstract object $A_{jj'}(sp)$ instead of object O_j,here sp was decided by input / output relationship $IM_j - AT_j - SP_j$.
6. Through connection gate transition $g(g \in g_{jj'})$ to connect om and $AO_{jj'}(sp)$ of O_j;
7. Use j' to place j, and back to (3).

In summary, if each activity transition and the gate of abstract sub-module object OCN is in the initial identification, through appropriate transition and the gate can be stimulated, it indicates there is no deadly embrace; similarly, if all the abstract sub-module objects can stimulate OCN, it indicates there is no deadly embrace abstract model.

2. Conflict Analysis

Abstracting model of the production system is highly abstract, and manufacturing system is the limited capacity of the resource allocation system, a resource may be object for a few services, but often only as a resource at the same time object for one service, which will lead to conflict occurred. In addition, some constraints of the system will lead to conflict. These conflicts can occur within OPN object (such as the number of simultaneous transitions at the same time only one can be stimulated), OPN may also occur in the mutual connection (as a time to the operation of two or more requests for the same resources). OPN on the abstract model for conflict analysis is intended to first identify all possible conflicts, and then offer all kinds of conflict most appropriate conflict resolution / decision-making programs to ensure the system agility, flexibility and reliability. In OPN, the conflict generally fall into two categories: input and output conflict [11].

1. input conflict: this kind of conflict happens when two or more transitions share the same input message place. (Figure 4(a) shows); or one transition has two or more input message places, and these input message places through ”(OR)” logic to connect with the transition(Figure4(b)shows). In the manufacturing system, several processing tasks competing for the same resource will enter the conflict.

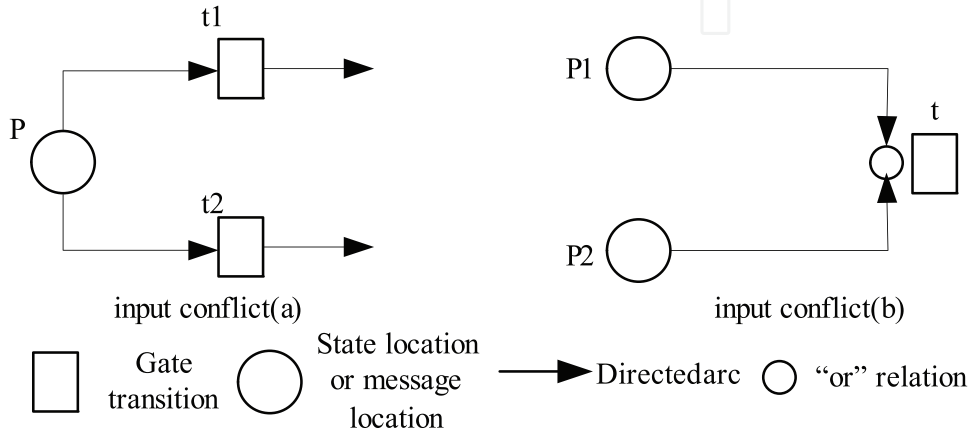

Fig. 4. A Petri net with input conflict

2. output conflict: this kind of conflict happens when one transition has two or more output message places,and the place through “(OR)” logic to connect with the transition(Figure 5 shows). In the manufacturing system, when the current processing is completed, there are several resources available to complete the next processing task, the output of conflict arises.

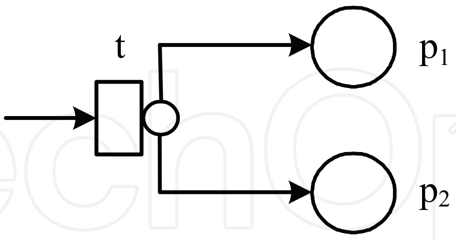

Fig. 5. A Petri net with output conflict

3. Conservation analysis

Conservation is another important feature of the model, as System resources are limited, if the model is not conservative, then the system exists overflow phenomenon, otherwise it will be security. According to the literature [14], when there is a P invariant for a non-negative integer vector x of $n \times 1$, so $x^T C = 0$ (C is the incidence matrix), then the Petri net is strictly binding. On the analysis of the actual situation, as long as the actual data system satisfies literature [14] required, then the Petri net is strictly binding, that is conservative and bounded, overflow phenomenon will not occur.

4. Production system objective function model based on PPOM

Owing to production system widely refers to the aspects of capacity, cost, stock and efficiency, etc, which covers a wide rage The following contents will only regard the capacity, which is mainly concerned by the companies, as the main study object, and build up the objective function model. According to the TOC theory, Bottleneck site or the capacity of bottleneck process decides the maximum capacity of production system. Detecting the bottleneck cell in time and improving its capacity are vital to capacity maximize and benefit maximize of the whole production capacity system.

4.1 Calculation of capacity

In the mass and single production enterprises, capacity is usually calculated in unit of the production cell or processing site. The equipment cells which constitutes the production cells have the nature of interchangeability, namely, any equipment in production cells can complete any same procedure assigned to this cell and meet its quality requirements. The calculation of production cell capacity is as follows [12]:

$$M = \frac{SF_e}{t} \tag{1.3}$$

$$t = \frac{1}{n}\sum_{i=1}^{n} t_i \cdot \theta_i \tag{1.4}$$

In the formula, M is the capacity of a production cell, Fe is the effective working time of one single equipment, S is the equipment number of a production cell, t is the average number of required equipments per hour of one single product, ti is the average number of required equipments per hour of No. I product in virtual factory, θ_i is the proportion of the output of No. I product in the planned total output, n is the variety number of products in virtual factory.
The effective working hours of production cell per day:

$$\varphi(\delta) = 8\,\delta \times (1 - \lambda) \tag{1.5}$$

Thereinto, λ is allowance rating (including allowance time like going to the WC, exercise during breaks and drinking,etc), δ is the frequency of the changing shifts of factory, in general, $\delta = \{1, 2, 3\}$, δ =1 means the factory takes the single shift producing mode. δ =2 means the factory takes the double-shift producing mode, δ =3 means the factory takes the three shifts producing mode.

$$F_e = (1 - ST - DT - PM - PC) \times \varphi(\delta) \tag{1.6}$$

In the formula (1.6), *ST* is the probability of Set up time occurs in the total working time per day, *DT* is the probability of Down time occurs in the total working time per day, PM is the probability of Preventive Maintenance time occurs in the total working time per day, *PC is* the probability of presupposed Protective capacity time occurs in the total working time per day.
From the formula (1.3) ~ (1.6) we can know:

$$M = \frac{S \times (1 - ST - DT - PM - PC) \times \varphi(\delta)}{\frac{1}{n}\sum_{i=1}^{n} t_i \cdot \theta_i} \tag{1.7}$$

In the actual production process, ST obeys the binomial distribution.
order $X = ST \sim B(n,p)$, then

$$f(x) = P(X) = C_n{}^x p^x q^{n-x} \tag{1.8}$$

thereinto $0 < p < 1,\ p + q = 1\ ,\ x = 0, 1, 2, \cdots, n$

As machines break down randomly in processing cell, it obeys the normal distribution commonly. Order $Y = DT \sim N\left(\mu, \sigma^2\right)$, so

$$f(y) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(y-\mu)^2}{2\sigma^2}} \quad , \ -\infty < y < +\infty \tag{1.9}$$

The routine preventive maintenance of enterprises includes week maintenance, mouth maintenance, season maintenance and year maintenance, get rid of producing anomaly, PM consistent with gamma distribution basically.order $Z = PM \sim Gamma(\beta, \alpha)$, then

$$f(z) = \begin{cases} \dfrac{\beta^{-\alpha} z^{\alpha-1} e^{-z/\beta}}{\Gamma(\alpha)} & z > 0 \\ 0 & others \end{cases} \tag{1.10}$$

thereinto, Γ is the gamma function, its expression is:

$$\Gamma(\alpha) = \int_0^{\infty} t^{\alpha-1} e^{-t}\, dt$$

For actual factory production, Protective Capacity PC corresponds to the Buffer builded up for Bottleneck process, order *f*(*q*) = *PC*, and then *f*(*q*) obeys the condition functions as follows:

$$f(q) = \begin{cases} q & if\ the\ \ production\ cell\ is\ bottleneck \\ 0 & others \end{cases} \tag{1.11}$$

Synthesize formula(1.8)~(1.11), we can conclude the capacity calculation formula of production cell is:

$$M = \frac{S \times [1 - f(x) - f(y) - f(z) - f(q)] \times \varphi(\delta)}{\frac{1}{n}\sum_{i=1}^{n} t_i \cdot \theta_i} \tag{1.12}$$

4.2 The expanding capacity analysis function

According to the actual production situation of factory, the equipment number, Protective Capacity, daily effective working hours, average number of required equipments per hour of each virtual product $\sum_{i=1}^{n} t_i \cdot \theta_i$, in a period of time, can be simplified as constants .Then build up the PPOM objective function model of capacity combines with the capacity calculation formula (1.12),

$$F_k = \frac{S_k \times [1 - f(x) - f(y) - f(z) - f(q)] \times \varphi(\delta)}{\frac{1}{n}\sum_{i=1}^{n} t_i \cdot \theta_i} \tag{1.13}$$

$$S.T.\begin{cases} f(x) = Cn^x p^x q^{n-x}, & x = 0,1,2,\ldots,n \\ f(y) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(y-\mu)^2}{2\sigma^2}}, & -\infty < y < +\infty \\ f(z) = \frac{\beta^{-\alpha} z^{\alpha-1} e^{-z/\beta}}{\Gamma(\alpha)}, & z > 0 \\ \varphi(\delta) = 8\delta \times (1-\lambda), & 0 < \lambda < 1 \\ \delta \in (1,2,3) & \\ k, i, \omega > 0, & 0 < \theta_i < 1 \end{cases}$$

4.3 Bottleneck detection cell based on PPOM

According to the capacity calculation objective function (1.13), combines with the historical data and actual situation of the factory, calculate the capacity of production cell 1:

$$f_1 = \frac{S_1 \times [1 - f_1(x) - f_1(y) - f_1(z) - f(q)] \times \varphi(\delta)}{\frac{1}{n}\sum_{i=1}^{n} t_i \cdot \theta_i}$$

Similarly, calculate the capacity of each production cell respectively:

$$f_2 = \frac{S_2 \times [1 - f_2(x) - f_2(y) - f_2(z) - f(q)] \times \varphi(\delta)}{\frac{1}{n}\sum_{i=1}^{n} t_i \cdot \theta_i}$$

$$\vdots$$

$$f_n = \frac{S_n \times [1 - f_n(x) - f_n(y) - f_n(z) - f(q)] \times \varphi(\delta)}{\frac{1}{n}\sum_{i=1}^{n} t_i \cdot \theta_i}$$

After that, using the simulated annealing algorithm and Matlab to write the programming code, making comparisons between f_1, f_2, $\cdots$, f_n respectively. According to TOC theory, define the minumum function of production cell as the bottleneck cell in the production process. This cell decides the maximum production capacity and actual production efficiency of factory. In the actual production process, we should meet the actual demand of bottleneck cell as far as possible and make efforts to improve its capacity.

5. The application of PPOM

5.1 The description of the power transformer production process in M company

M company was founded in August 1999,it was invested a total investment of 30 million U.S. dollars by A company ---- the top 500 enterprises in the world, as the third power transformers joint venture established in China. Its main business is to design, product, sale and maintain of 110KV/220KV medium and large power transformer. In 2008, M company’s sales revenue had been reached more than 1.4 billion Yuan and the production capacity had been reached 12000MVA with more than 460 employees. The M company had also received the awards of The Top 100 Electric Company in China, and had been selected as the Top Ten Growth Competitiveness Enterprises of China's Electric Power Industrial. In 2009, as the company undertook parts of the national power grids’ alteration and Wenchuang earthquake reconstruction projects, its production order number had jumped to 64 per year, the annual effective capacity requisition had reached to 15160 MVA.

Here we will take the most representative product 240MVA/220KV transformer of this company as the example to analyze. The production process of Power transformer starts from raw material, and through cells of Coil Winding, High Frequency Welding (HFW),

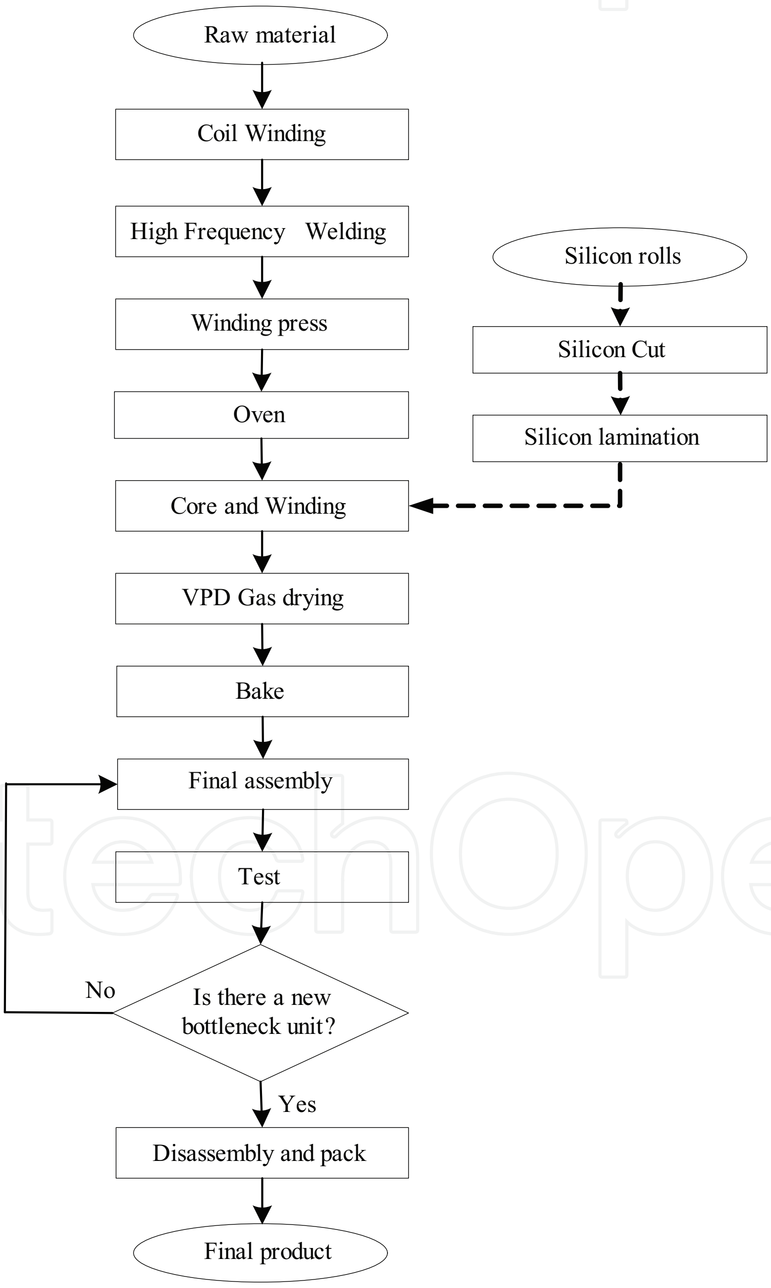

Fig. 6. Power Transformer production process of M company

Coil Oven, Iron Cut, Iron Lamination, Down-lead, Walkthrough, Core, Winding Assembly, Oven, Final Assembly, Test, Pack, etc. Then is the finally transformer. The production process of Power transformer in M company shown in Figure 6.

5.2 Power transformer production abstract model based on PPOM

5.2.1 Power transformer production abstract model

For the actual situation of M company power transformer production, use PPOM method, we can abstract raw material warehouse, coil winding cell, HFW cell, Winding press cell, Coil Oven cell, Winding assembly cell, Iron Cut cell, Iron Lamination cell, Down-lead Walkthrough cell, Core and Winding Assembly cell, Oven cell, Final Assembly cell, Test cell and knocked-down packing cell to 14 place sub-module P_1 ~ P_{14},then optimize these 14 place sub-modules according to production process, and build M company power transformer production abstract model, as shown in figure 7.

The particularization for each place and transition in figure 7 are shown as table 1.

5.2.2 Power Transformer production abstract model capacity analysis

1. deadly embrace analysis

The occurrence of deadly embrace would lead to suspension of the entire power transformer production abstract model system running and seriously affect system capacity. Therefore,

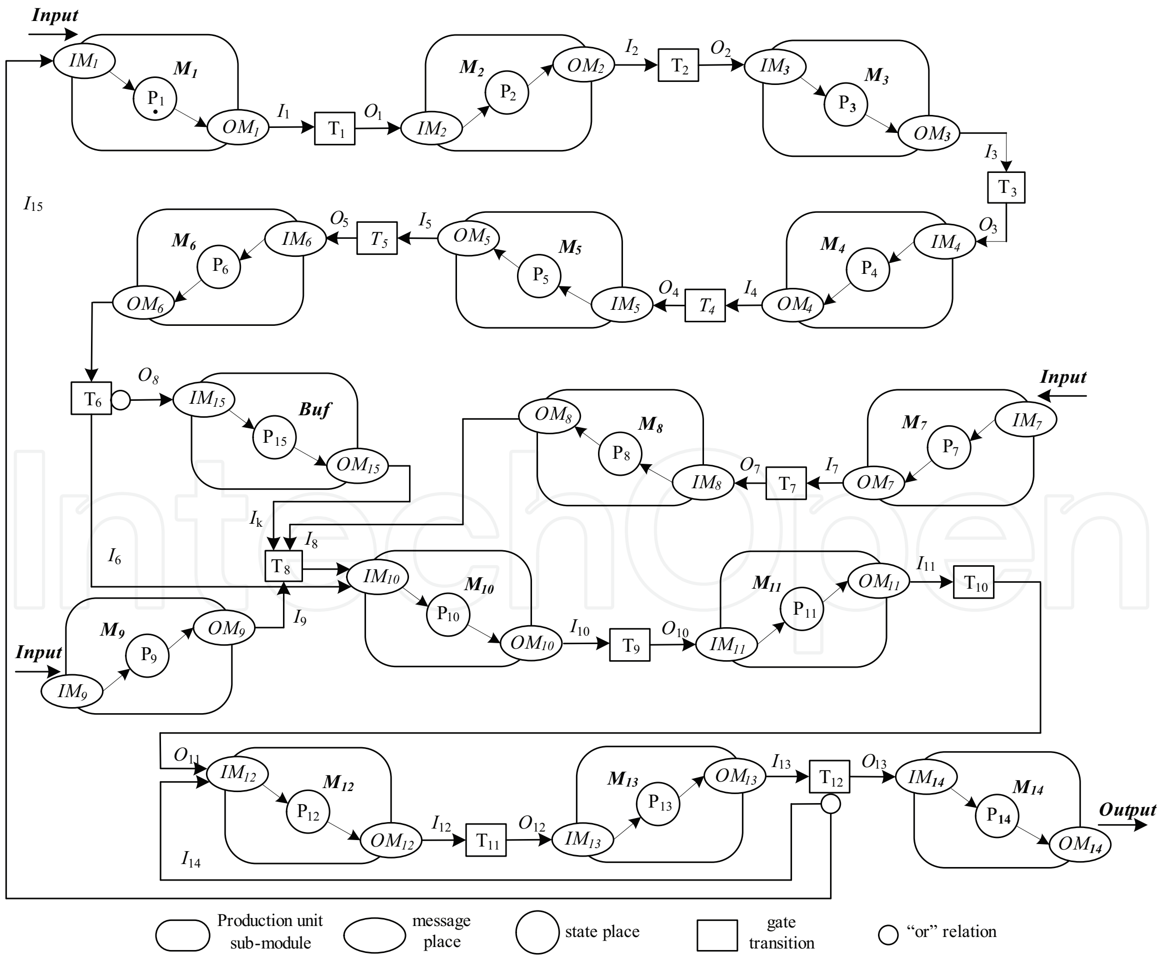

Fig. 7. Power Transformer production abstract model based on PPOM

Production cell	mean	place	mean	transition	mean
M1	Raw material storage	P1	Transformer material preparing	T1	Material has been prepared
M2	Coil Winding	P2	Vertical and Horizontal winding	T2	Coil winding finished
M3	HFW	P3	High winding HFW	T3	High winding HFW finished
M4	Winding press	P4	Winding press size adjustment	T4	Press finished and prepared to oven
M5	Coil Oven	P5	Coil to oven	T5	Coil oven finished and prepared to assembly
M6	Winding assembly	P6	Coil assembly	T6	Coil assembly finished,goes to Core and Winding Assembly or Buffer Core and Winding Assembly
M7	Iron Cut	P7	Georg cut	T7	Iron Cut finished
M8	Iron Lamination assembly	P8	Iron Lamination	T8	Lamination Finished and enter to Core and Winding Assembly worktable
M9	Down-lead Walkthrough	P9	Down-lead Walkthrough	T9	Core and Winding Assembly finished and prepared to VPD
M10	Core and Winding Assembly	P10	Core and Winding Assembly	T10	Out of oven and prepared to Final Assembly
M11	VDP Oven	P11	VDP Oven	T11	Final Assembly finished and prepared to test hall
M12	Final Assembly	P12	Final Assembly	T12	Transformer test finished,if it up to grade,goes direct to knocked-down packing;if not,back to transfomer final Assembly cell to re-assembly or roll to coil cell to re-coil
M13	Test	P13	Transformer capacity test		
M14	knocked-down packing	P14	knocked-down packing pre-rollout		
Buf	assembly buffer cell	P15	Assembly buffer		

Table 1. Meaning of places and transitions in Fig.7

after the power transformer production process $PPOM-T$ model is established, the system must determine whether there exists deadly embrace, and find out all possible deadly embrace situation, to avoid its occurrence before the excitation system controls. For convenience, OCN incidence matrix of the transformer production process $PPOM-T$ model and initial marking are listed in tabular form, as shown in Table 2.

Set the following stock preparation module T_1 transition of power transformer production raw materials as an example, use Invariant theory: $vC=0$, $im=im_0$ (v is p invariant, C is the incidence matrix)to do capacity analysis.

Incidence matrix between power Transformer production $PPOM-T$ model place and transitions is $C=[c_{ij}]_{15\times 12}$, thereinto:

C	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8	T_9	T_{10}	T_{11}	T_{12}	m_0
P_1	-1	0	0	0	0	0	0	0	0	0	0	-1	1
P_2	1	-1	0	0	0	0	0	0	0	0	0	0	0
P_3	0	1	-1	0	0	0	0	0	0	0	0	0	0
P_4	0	0	1	-1	0	0	0	0	0	0	0	0	0
P_5	0	0	0	1	-1	0	0	0	0	0	0	0	0
P_6	0	0	0	0	1	-1	0	0	0	0	0	0	0
P_7	0	0	0	0	0	0	-1	0	0	0	0	0	0
P_8	0	0	0	0	0	0	1	-1	0	0	0	0	0
P_9	0	0	0	0	0	0	0	-1	0	0	0	0	0
P_{10}	0	0	0	0	0	1	0	1	-1	0	0	0	0
P_{11}	0	0	0	0	0	0	0	0	1	-1	0	0	0
P_{12}	0	0	0	0	0	0	0	0	0	1	-1	-1	0
P_{13}	0	0	0	0	0	0	0	0	0	0	1	-1	0
P_{14}	-1	0	0	0	0	0	0	0	0	0	0	1	0
Buf	0	0	0	0	0	1	0	-1	0	0	0	0	1

Table 2. OCN matrix of transformer abstract model

$$c_{ij} = c_{ij}^{+} - c_{ij}^{-}, \quad i \in \{1,2,...,15\},\ j \in \{1,2,...,12\},$$

$$c_{ij}^{+} = \begin{cases} 1 & (t_j, p_i) \in F \quad i \in \left\{1,2,\cdots,15\right\}, j \in \left\{1,2,\cdots,12\right\} \\ 0 & others \end{cases}$$

$$c_{ij}^{-} = \begin{cases} 1 & (p_i, t_j) \in F \quad i \in \left\{1,2,\cdots,15\right\}, j \in \left\{1,2,\cdots,12\right\} \\ 0 & others \end{cases}$$

So, the incidence matrix C

$$C = \begin{bmatrix}
-1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 \\
1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & -1 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & -1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & -1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & -1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & -1 & -1 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & -1 \\
-1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 & -1 & 0 & 0 & 0 & 0
\end{bmatrix}$$

From Invariant theory,we can get OCN incidence matrix of power Transformer production abstract model is $rank(C)=15$,from $x^T m = x^T m_0$ (x is the vector of $n \times 1$, m_0 is Initial state) gets,all the m can be reached by m_0.
From Petri net definition identification knows, $m(P_i)$ shows the number of tokens in P_i.so $m(P_1)=1, m(P_1)+m(P_2)+\cdots m(P_{14})+m(IM_1)-m(OM_2)+\cdots+m(IM_{14})-m(OM_{14})=0(X)$, now T_1 can be stimulated.
Similarly, other transitions T_2, T_3 …, T_{14} of Power Transformer production abstract model OCN in the initial identification m_0, through appropriate action all can be stimulated, thus shows the power transformer production abstract model exists no deadly embrace.

2. Conflict analysis

In the power transformer production abstract model petri net, the abstract model PPOM-T is a highly abstraction of transformer production system, while in the production process, between the production processing cells or working procedures, production capacity can be of different sizes, time differences, which leads to conflict. In addition, certain constraints of the system, such as materials needed for the transformer production, aid tools, staff and other resources may service for a few sets in the production of transformer, will lead to conflict.in the power transformer production PPOM-T model, transiton T_{12} exists output conflict, as shown in Figure 8.

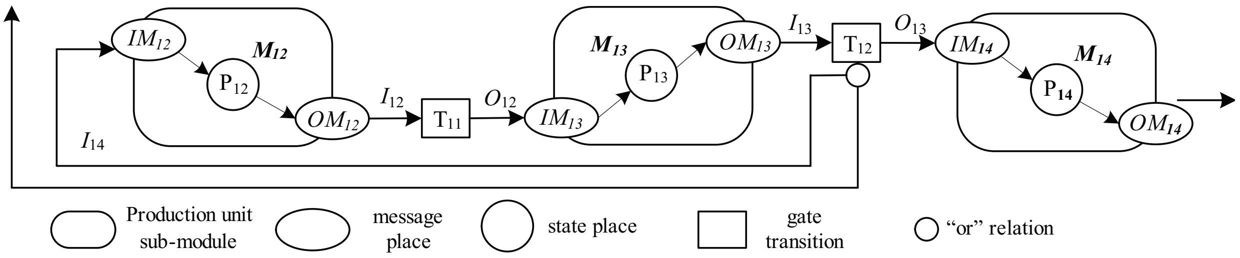

Fig. 8. A conflict model in T_{12}

As the power transformer production system is a complex system, when it encounter conflicts, the system should be based on characteristics of power transformers and the actual production and use appropriate conflict resolutiono in a timely manner.as Figure 8 mentioned above, transition T_{12} exists output conflict,we can adopt the follow-up working procedure minimum priority principle,give priority to follow-up working procedure minimum production cell M_{12},that is returned to transformer final assembly cell to re-assembly for those which can not meet test capacity requirements of components; and then consider the cell M1 (it has the most follow-up working procedures).

3. Conservation Tests

Conservation analysis is another important feature of the model, it shows whether the system exists overflow phenomenon and security. According to the literature [14], when there is a P invariant for a non-negative integer vector x of $n \times 1$, so $x^T C = 0$ (C is the incidence matrix), then the Petri net is strictly binding, that is conservative and bounded, overflow phenomenon will not occur.

$$
if\ x^T \cdot \begin{bmatrix}
-1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 \\
1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & -1 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & -1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & -1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & -1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & -1 & -1 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & -1 \\
-1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 & -1 & 0 & 0 & 0 & 0
\end{bmatrix} = 0,\ then
$$

Non-zero positive vector $x^T = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 6 & 1 & 2 & 1 & 1 & 1 & 2 \end{bmatrix}$, so that $x^T C = 0$.

Therefore, this power transformer production abstract model exists $x^T = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 6 & 1 & 2 & 1 & 1 & 1 & 2 \end{bmatrix}$, so that $x^T C = 0$. From this we know, the power transformer production process abstract model object OCN is conservation bounded, overflow will not occur, and the model has good performance.

5.3 The objective function model of the power transformer

According to M company's power transformer's actual production situation, combines with the capacity calculation formula (1.13), the objective function model of the power transformer can be built up as:

$$
F_{PPOM-Tk} = \frac{S_k \times [1 - f(x) - f(y) - f(z) - f(q)] \times \varphi(\delta)}{\frac{1}{n}\sum_{i=1}^{n} t_i \cdot \theta_i} \tag{1.14}
$$

$$
S.T. \begin{cases}
f(x) = C_n{}^x p^x q^{n-x}, & x \in \{0, 1, \cdots, n\} \\
f(y) = \dfrac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(y-\mu)^2}{2\sigma^2}}, & -\infty < y < +\infty \\
f(z) = \dfrac{\beta^{-\alpha} z^{\alpha-1} e^{-z/\beta}}{\Gamma(\alpha)}, & z > 0 \\
f(q) = q, & 0 \le q < 1 \\
\varphi(\delta) = 8\,\delta \times (1 - \lambda), & \delta \in \{2\} \\
k, i, \omega > 0, \quad 0 < \theta_i, \lambda < 1 &
\end{cases}
$$

Thereinto, S_k is the equipment number contained by the production cell, $f(x)$ is the distribution function of Set up time, $f(y)$ is the distribution function of Down time, $f(z)$ is the distribution function of Routine maintenance time , $\varphi(\delta)$ is the function of the daily effective working hours of production cell, λ is allowance rating (including allowance time like going to the WC, exercise during breaks and drinking,ect) , δ is the frequency of changing shifts of factory, t_i is the average number of required equipments per hour of No.i product in virtual factory, θ_i is the proportion of the output of No.i product in the planned total output, ω is the variety number of products.

5.4 Power transformer to detect the production process bottleneck cell

In the Period of time, the number of equipment per production process cell, protective capacity, the effective working hours per day and average number of required equipments per hour for virtual product $\sum_{i=1}^{n} t_i \cdot \theta_i$, Can be considered as constant to simplify handling.

oder
$$t_k = \frac{1}{n}\sum_{i=1}^{n} t_i \cdot \theta_i \tag{1.15}$$

$$\psi_k = f(x) + f(y) + f(z) + f(q) \tag{1.16}$$

And as $\varphi(\delta) = 8 \times 2 \times (1 - 15\%) = 13.6$ h

Use the formula (1.15) (1.16) into formula (1.14) can make power transformer production capacity objective function model (1.14) simplified to:

$$F_k = \frac{13.6 S_k \times (1 - \psi_k)}{t_k} \tag{1.17}$$

$$S.T.\begin{cases} \psi_k = f(x) + f(y) + f(z) \\ t_k = \frac{1}{n}\sum_{i=1}^{n} t_i \cdot \theta_i \\ 0 < f(x), f(y), f(z) < 1, x, z, k, t, n > 0, y \in R \end{cases}$$

Then, using the simulated annealing algorithm in the production function to calculate the minimum producion capacity, that is the bottleneck of the production process cell.

1. Solution space: Solution space S is just counted once for each site,is a set of all permulations of $k \in \{1, 2, \cdots, 15\}$, the members of s denoted by $(s_1, s_2, \cdots, s_{15})$,and notes s_{n+1}=s_1 , optional for the initial solution can be $(1, 2, \cdots, 15)$.
2. objective function: defining transformer capacity function as cost function
$$F(s_1, s_2, \cdots, s_{15})_k = \frac{13.6 S_k \times (1 - \psi_k)}{t_k} \tag{1.18}$$
3. difference cost function: set $(s_1, s_2, \cdots, s_{15})$ transformed to $(\eta_1, \eta_2, \cdots, \eta_{15})$,then the difference cost function is
$$\Delta F = F(\eta_1, \eta_2, \cdots, \eta_{15}) - F(s_1, s_2, \cdots, s_{15}) \tag{1.19}$$

Use Matlab Write code as follows:

```
begin
init-of-T; { T is Initial temperature}
 S={1, 2, …,15}; {S is Initial value}
 termination=false;
 while termination=false
   begin
     for i=1 to L do
       begin
         generate(S′form S); { from the current loop circuit S to generate new S'}
         Δt:=F(S′))-F(S);{ F (S) is capacity value for each site}
            if(Δt<0) or (exp (-Δt/T)>Random-of-[0,1])
         S=S′;
       if the-halt-condition-is-TRUE THEN
       termination=true;
     End;
     T_lower;
   End;
End
```

After using the simulated annealing algorithm, it can quickly detect the minimum production process capacity, as winding assembly is the Z power transformer company's capacity bottleneck cell of production system.

5.5 The proposion of improvement measures

As the daily capacity of production cell of Winding assembly is:

$$F(s_6) = \frac{13.6 S_6 \times (1-\psi_6)}{t_6} = \frac{13.6 \times 4 \times (1-13.8\%)}{229.67} = 0.204 \text{ (unitage/day)}$$

Take the product 240MVA and the annual working days as 250 days for Calculation, the annual production capacity cell of Winding assembly is

$$F_Y(s_6) = 0.204 \times 250 \times 240 = 12250.48 \text{ (MVA/year)}$$

Obviously, the calculation of the annual production capacity cell of Winding assembly $F_Y(s_6)$ is less than the M company's actual required annual production capacity of 15160 MVA. According to the actual situation of the enterprise, the Winding assembly cell takes the early, middle and late three shifts, thereby, the daily production capacity cell of Winding assembly can be calculate out:

$$F^{'}(s_6) = \frac{S_6 \times (1-\psi_6) \times 8 \times 3 \times (1-15\%)}{t_6} = \frac{4 \times (1-13.8\%) \times 20.4}{229.67} = 0.306 \text{ (unitage /day)}$$

The annual production capacity cell of Winding assembly is:

$$F_Y^{'}(s_6) = 0.306 \times 250 \times 240 = 18375.72 \text{ (MVA/year)}$$

At this point, the annual production capacity cell of Winding assembly of 18375.72MVA was greater than the actual requirements of the 15160 MVA, the capacity requirements problem was resolved. At the same time, the capacity bottleneck might be transferred to other production cells, therefore, the changed actual data is needed to re-simulated annealing calculation (shown in Figure 7), and analyze the capacity of the possible new bottleneck cells, taking the improvement measures for these new bottleneck capacity cell and recycling until all production capacity cells have meet the actual requirements

5.6 The results of improvements

After the PPOM method had been implied in M company, we detect the bottleneck production capacity cell, proposed improvement measures in time and made the annual production capacity of Winding assembly cell increased $(76.5-57.8)\div 57.8=\ 32.47\%$ than the original annual production capacity of 57.8 , besides, the production cycle time TPT was shortened correspondingly. Concrete results are shown in Table 3.

Items	Before improvement	After implied PPOM	Effects
Production cycle time TPT(h)	724.1	646.4	77.7
Annual production capacity	57.8	76.5	18.7
Increased production efficiency per year (million)	— —	— —	202.14

Table 3. Effect statistics

1. The average production cycle time of each power transformer reduced 77.7h;
2. The production capacity increased 32.47%;
3. The production efficiency increased 2.0214 million Yuan per year.

6. Conclusion

Each production system will has the minimum capacity bottleneck site, which restricted the production system to further enhance the capacity, it is important for production scheduling at the bottleneck core site. In this paper,combine with Petri net technology, OO method and agile manufacturing ideas, put forward agile production scheduling PPOM, described using capacity bottleneck core site as the scheduling core and to the other times (or re) production bottleneck site divergence PPOM production scheduling model method, and finally through empirical research methods to further validate correctness and feasibility of PPOM. The method extends the traditional capacity calculation function model and is closer to actual production, the enterprise production process model are of considerable practical value.

PPOM method of the production process for the manufacturing enterprise model provides a scientific basis and an operational new method,it is an exploratory study focuing on manufacturing production process model,for sub-modules internal computing methods of the PPOM abstract model and existing ERP system links and PPOM information system development, also need to produce in-depth exploration of the actual situation..

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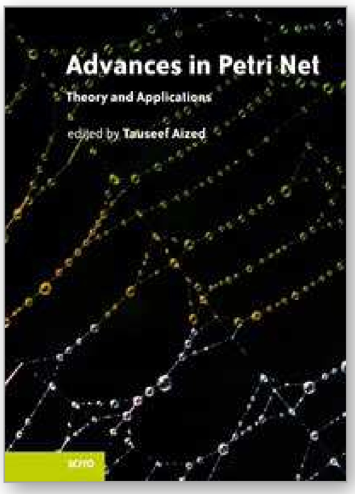

Advances in Petri Net Theory and Applications
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The world is full of events which cause, end or affect other events. The study of these events, from a system point of view, is very important. Such systems are called discrete event dynamic systems and are of a subject of immense interest in a variety of disciplines, which range from telecommunication systems and transport systems to manufacturing systems and beyond. There has always been an intense need to formulate methods for modelling and analysis of discrete event dynamic systems. Petri net is a method which is based on a well-founded mathematical theory and has a wide application. This book is a collection of recent advances in theoretical and practical applications of the Petri net method and can be useful for both academia and industry related practitioners.

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