An Intelligent Prediction Model for Bottleneck in Production System Based on Cloud Manufacturing

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Abstract. The maximum output of manufacturing systems depends on the production capacity of bottleneck. So it is very important to predict abottleneck unit before actual production. However, the bottleneck often shifts from one place to another, it is difficult to predict accurately. To solve this problem, an intelligent prediction model based bottleneck (IPMFB) method is proposed by combining petri nets, object-oriented technology and cloud manufacturing ideas. With the proposed method, process and rules are designed, and a simulation model is established by the Plant Simulation software. Then all production data are input into the simulation model to intelligently predict the bottleneck by cloud computing and simulation running. In addition, the IPMFB method gives priority to production resources scheduling for bottleneck, which can satisfy a demand of bottleneck firstly by dynamic programming and a fuzzy algorithm. Finally, the validity and feasibility of the IPMFB method are verified by empirical research.

Keywords: Intelligent prediction modeling · Production scheduling · Virtual simulation · Petri nets · Cloud manufacturing

1 Introduction

The Fourth Industrial Revolution is coming, which holds the promise of increased flexibility in manufacturing, along with mass customization, better quality, and improved productivity [1]. As a new service-oriented networked manufacturing mode [2], cloud manufacturing provides a new idea for the upgrading of manufacturing and plays an important role in Industry 4.0.

According to the theory of constraints (TOC) [3], the maximum output of manufacturing system depends on the production capacity of bottleneck unit [4]. When the demand is larger than the capacity, there will be at least one bottleneck in the production process, and the bottleneck often shifts from one place to another at different times [5]. Therefore, it is significant to predict the bottleneck unit in advance to maximize the benefit of the production system [6].

Several solutions have been proposed to predict production bottleneck, such as a novel Parallel gated recurrent units (P-GRUs) network are particularly developed for

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shifting bottleneck prediction [7], a Heuristic algorithm of production process optimization for dynamic bottleneck to determine the bottleneck machine [8], and a genetic algorithm based machining scheduling is proposed to optimize the key bottleneck process[9]. In recent years, some simulation tools have been developed for the prediction of bottleneck units. For instance, the FLEXSIM software has been utilized to identify the bottleneck process [10], the SIMOGRAMS method has been used to locate the bottleneck workshop and improve the bottleneck cell [11], and the MATLAB tool has been put into practice to detect the bottleneck for production system [12]. However, these methods are either complex or nonvisual.

Therefore, a new virtual prediction method for bottleneck is proposed to shorten the production cycle time and increase the system capacity, based on Petri nets, object-oriented technology and cloud manufacturing.

2 Methodology

2.1 Conception

Intelligent Prediction Modeling for Bottleneck (called IPMFB) is a new predicting approach, which combines petri nets, object-oriented and cloud manufacturing to abstract the processing units as cloud places, and integrate the places into the cloud computing. Then the virtual simulation model is designed to intelligently predict the bottleneck unit before actual manufacturing. Furthermore, the production resource of bottleneck is satisfied firstly to shorten the total production time and increase the system production capacity.

2.2 Definition

Therefore, the model of intelligent prediction process of bottleneck can be defined as shown below [13]:

$$PN = \{P,\ \ T,\ F,\ \ K,\ \ W,\ \ M_0\}$$

Where *(P, T, F)* is a basic Petri net model,

$W{:}F \rightarrow \{1,2,3,\ldots\}$ is a weighted function,

$K{:}S \rightarrow \{1,2,3,\ldots\}$ is a capacity function,

$M{:}S \rightarrow \{1,2,3,\ldots\}$ is a marking of *PN,*

The constraints: $\forall s \in S : M(s) \leq K(s)$.

According to the definition, the IPMFB can be stated as Fig. 1 shows:

2.3 Process

IPMFB method is an intelligent prediction for bottleneck in virtual manufacturing system. The process is designed as Fig. 2 shows:

According to the TOC theory, one man-hour loss of bottleneck can lead to one man-hour loss of system [14]. IPMFB method gives priority to the production resources scheduling of bottleneck, which can satisfied the demand of bottleneck firstly, so as

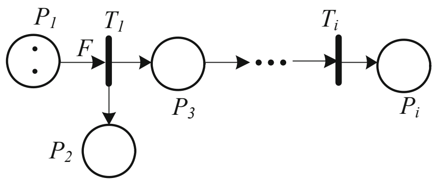

Fig. 1. Sketch of IPMFB

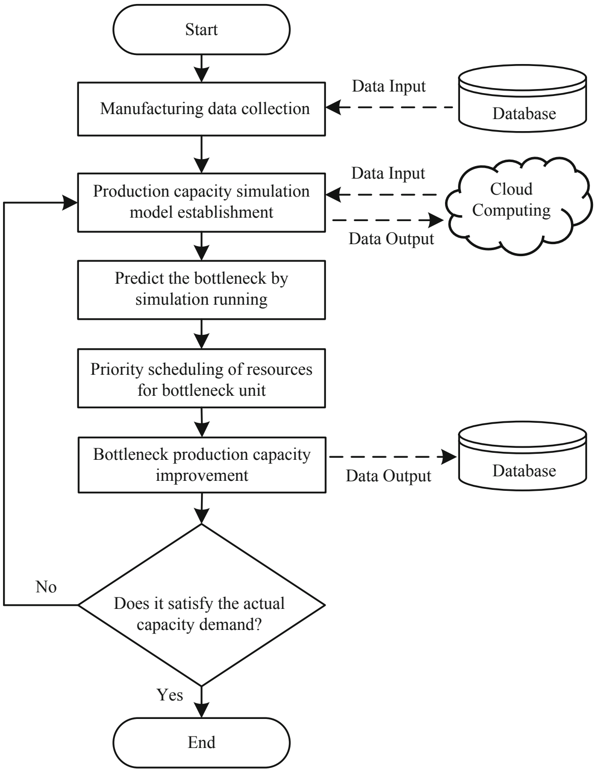

Fig. 2. Process of IPMOB

to ensure the maximum capacity and profit of the system. Figure 3 shows the rules of resources scheduling based on bottleneck.

From Fig. 3, the circles are processing units, the rectangles are buffers, and the ellipses are message passing of input or output.

The rules of resources scheduling based on bottleneck are described as follows:

1) Find out the bottleneck unit, suppose the bottleneck unit is P_{n2};
2) Give priority to the resources scheduling of P_{n2};
3) Subsequent processing units (such as P_n, P_{n1}) should change their job sequencing and resource allocation based on the P_{n2} resource scheduling;

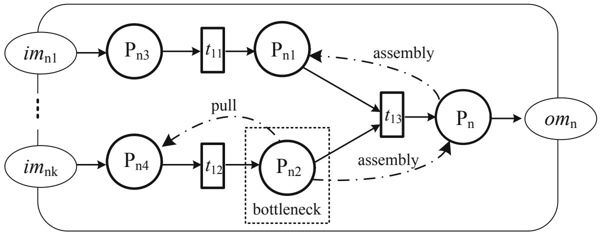

Fig. 3. Rules of resources scheduling based on bottleneck

4) Former processing units (such as P_{n4}) should adopt the pull production to rearrange production plan and redistribute resources according to the resources scheduling results of P_{n2}.

2.4 Function Model of Resources Scheduling

Assuming there are k resources in a factory, which should be delivered to s processes, and there are n criteria for the scheduling results. Thus, a fuzzy dynamic programming model with n objectives in k dimensions can be established as follows:

1) Set up a function model for resources scheduling

$$\begin{aligned}&\left((s+1)u^1, (s+1)u^2, \cdots, (s+1)u^k\right)\\&=\left(su^1 - sv^1, su^2 - sv^2, \cdots, su^k - sv^k\right);\end{aligned} \tag{1}$$

Decision variable:

$$\begin{aligned}&sv\left(su^1, su^2, \cdots, su^k\right) = \left\{(sv^1, sv^2, \cdots, sv^k)\,\middle|\,0 \le sv^1 \le su^1,\right.\\&\left.0 \le sv^2 \le su^2, \cdots, 0 \le sv^k \le su^k, \left(sv^1, sv^2, \cdots, sv^k\right) \in \left\{d_j\right\}\right\}\end{aligned}$$

where s is the stage variable to deliver resources for processes, $(su^1, su^2, \ldots, su^k)$ is the state variable and su^k is the quantity (or ratio) of k^{th} resource distributed from process 1 to process s. $(sv^1, sv^2, \ldots, sv^k)$ is the decision variable and sv^k is the quantity(or weight) of k^{th} resource allocated for process s.

2) Establish an objective function model for resources optimal scheduling.

According to the principle of fuzzy optimization [15], the relative membership degree is expressed as (2).

$$sd_j^k = \frac{1}{1 + \left[\frac{\sum_{i=1}^{m}\left[w_i\left(g_i - sMr_{ij}^k\right)\right]^p}{\sum_{i=1}^{m}\left[w_i\left(sMr_{ij}^k - b_i\right)\right]^p}\right]^{\frac{2}{p}}} \tag{2}$$

where p is the distance parameter.

According to the maximum membership principle of fuzzy set, the objective function model of resource scheduling based on fuzzy dynamic programming is defined as (3).

$$F = \max \sum_{k=1}^{K} \sum_{s=1}^{S} d[v_k(s)] \tag{3}$$

Where F is the maximum objective function, $d\left[v^k(s)\right]$ is the membership value that obtained from the decision value and the membership degree($su^k{}_j$), when the decision value of k dimension is $v^k(s)$ in the stage s.

2.5 Simulation

By using the simulation software, the manufacturing system simulation model is designed to simulate the real production situation.

Then the capacity data and rules of resources scheduling are input in simulation model, so as to predict the bottleneck intelligently through cloud computing and simulation running.

At last, the bottleneck unit will be improved by the maximum membership principle of resource scheduling fuzzy set to increase system capacity and economic benefits.

3 Experiments

3.1 Case Description

The annual production capacity of Z Company is 56 sets of 500 kilovolt ampere transformers. As the company has received some transformer orders from the State Grid, the capacity demand rises to 64 sets per year. So it is urgent to enlarge the production capacity, especially in its core workshop-coil winding. Therefore, it is very important to predict the bottleneck unit of coil winding workshop in advance.

3.2 The Initial Simulation Model

The coil winding workshop mainly includes seven units: vertical winding, horizontal winding, coil demoulding, coil welding, coil assembly, drying and coil inspection [16]. The initial intelligent prediction simulation model is established by Plant Simulation software as Fig. 4 shows.

3.3 Simulation Running and Result Output

All actual production data of the company are input in the simulation model to get the annual capacity of each processing unit by cloud computing and simulation running.

From Table 1, it can be seen that the capacity of coil assembly is the smallest unit in the manufacturing. So the coil assembly is the bottleneck unit of the system, and the resources must be satisfied firstly in production scheduling.

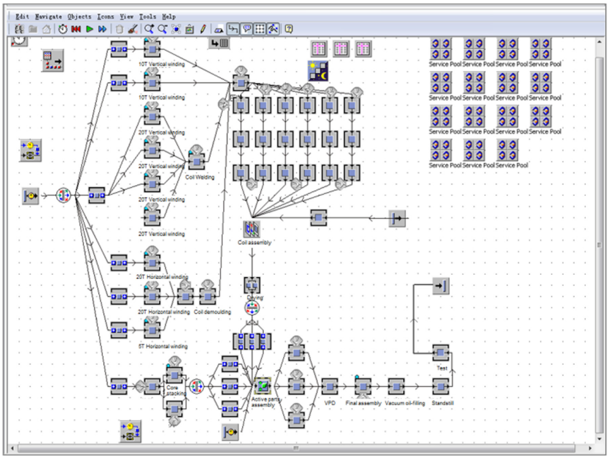

Fig. 4. The initial simulation model

Table 1. The annual capacity of each processing unit

No.	Processing unit	Annual capacity (Sets/a)
1	Vertical winding	67.2
2	Horizontal winding	75.5
3	Coil demoulding	98.8
4	Coil welding	67.4
5	Coil assembly	57.8
6	Drying	84.7
7	Coil inspection	75.5

3.4 Priority Scheduling of Resources for Bottleneck

In order to simplify the calculation, only three bottleneck processes in the coil winding workshop are analyzed, that is, S1 is the key bottleneck, S2 is the second bottleneck, and S3 is the third bottleneck.

According to the practical experience, production scheduling is mainly to optimize 5 kinds of resources.

1) Workgroup: 10 workgroups with 4 operators per group are assigned for processes S1, S2 and S3.
2) Forklift: 12 forklifts for processes S1, S2 and S3.
3) Insulating parts: about 320 kg.
4) Management intensity: the key bottleneck, the first intensity.
5) Environmental comfort: the key bottleneck, the first comfortable.

Both management intensity and environmental comfort are qualitative indicators, so they can be regarded as a unit "1". In the next step, they should be calculated by their weights.

$$\sum_{i=1}^{3} k4 = 1; \qquad \sum_{i=1}^{3} k5 = 1$$

Therefore, the five kinds of resources in winding workshop are defined as follows:

$$k1 = 10,\ k2 = 12,\ k3 = 320,\ k4 = 1,\ k5 = 1.$$

Through formula (3), the objective function value can be calculated by cloud computing.

$$F = \max \sum_{k=1}^{K} \sum_{s=1}^{S} d[v_k(s)] = 9.813$$

And the optimal resource scheduling is solved by dynamic programming and fuzzy algorithm as Table 2 shows.

Table 2. Optimal resources scheduling plan

No.	Production resources	Process S1	Process S2	Process S2	Relative membership degree
1	Workgroup	6	2	2	1.954
2	Forklift	5	4	3	1.968
3	Insulating parts	227	57	35	2.057
4	Management intensity	0.63	0.27	0.10	1.933
5	Environmental comfort	0.42	0.37	0.21	1.901

3.5 The Improved Simulation

After the resources are scheduled preferentially for the bottleneck with dynamic programming and fuzzy algorithm, the simulation model need to be redesigned as Fig. 5 shows:

3.6 Experimental Results

From Table 3, it can be seen that the annual capacity of coil assembly is increased to 64 sets, which is 10.73% higher than before. And the increased profits are more than 2,020,000 RMB per year. The bottleneck improvement effect is very significant.

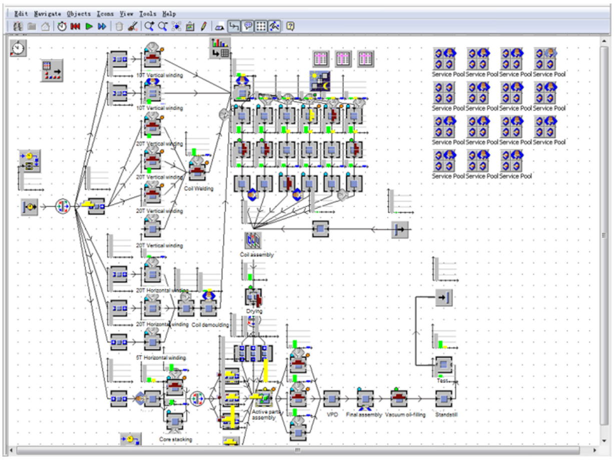

Fig. 5. The improved simulation model

Table 3. Evaluation of improvement

No.	Items	Before	After	Effect
1	Annual capacity (Sets/a)	57.8	64	10.73%
2	Increased profits (RMB/a)	–	–	2,020,000

4 Conclusion

In this paper, a new approach is proposed to predict the bottleneck, based on Petri nets, object-oriented and cloud manufacturing ideas. Firstly, the process and rules of IPMFB are designed. Then the intelligent prediction simulation model is established by Plant Simulation software, and all production data are input in the model to predict the bottleneck by cloud computing and simulation running. Moreover, the IPMFB method gives priority to the production resources scheduling of bottleneck, which can satisfy the demand of bottleneck firstly by dynamic programming and fuzzy algorithm. Finally, the validity and feasibility of the IPMFB method are verified by the empirical research.

In the future, we plan to add the deep learning algorithm of artificial intelligence into the simulation model to improve the intelligence of prediction.

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