Manufacturing System Coordinated Optimization Model and Its Application

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Abstract—An kind of operation optimization model is put forward on the basis of analyzing manufacturing system characteristics with consideration of optimization. The Features of the model are real-time, dynamic, multi-objective and multistage. The algorithm called ‘Harmonizing Cluster Results’ for the model is presented in order to solve the difficulties of solution for the manufacturing system operation model. Then the model is simplified into some different submodels, such as production ability optimization submodel, time optimization submodel, balancing and harmonizing submodel etc. These submodels include different optimization directions which covers Time, Quality, Cost, Service and Environment of manufacturing system. Finally the operation optimization model and its solution algorithm are proved to be reasonable and available applied to an assembly line of energy meter in a factory. The simulation results showed the solution algorithm of the model is accurate.

Keywords—manufacturing system; coordinated optimization model; multi-objective simulation optimization model

I. INTRODUCTION

Although the Lean Production has been put forward for a long time, the actual operation of production system doesn’t meet the requirement of Lean Production in many enterprises. Aiming at above phenomena the enterprises and the Academia do a lot of research work in order to make production system operation meeting Lean Production. Only through the establishment and use of theoretical model can we set up the effective mode of production operation systems to achieve the purpose of the system—lowest cost, largest profit, reasonable allocation of resources and efficient system operation. For this reason many domestic and foreign scholars have done a lot of research in the relevant aspects. Zhu Jianying[1] has studied the model of the modern manufacturing systems, modeling method and the new development of key technologies, he summarized the modern manufacturing system models and modeling methods as well as discussed the key technologies and the development direction. As to the operation model, Huang He, Liu Fei[2] have studied the network sales operation model, discussed the structure, operating model and control management of the A2C & D2C network sales operation model. Reference literatures [3-5] illustrate the production system monitoring and diagnostic techniques, production systems optimized scheduling algorithm, production control, simulation and optimization, and other related aspects. In workshop production, references[6-8] proposed modular Lean production organizations to support the process. Based on the principle of modular Lean Production, they analyzed the organizational model of the lean production in depth, proposed the assessment means for the level of the production model. Ranky, Paul G[9] studied the balance coordination algorithm in the digital simulation model of the workshop and internal corporate networks in the lean production system, a distributed, network-based architecture is proposed to maximize the profits of production systems operation. They also give the obeying rules and laws so the information acquired for such systems is qualified. Papadopoulos HT[10] proposed the original model Management System for the production system design and operation, the models vary according to the different types of production systems and the application of technologies. Taylan O.[11] studied the neuro-fuzzy model and its performance evaluation of the dynamic production system, established the fuzzy model of the production process, the artificial neural network architecture and algorithm of the multi-layer perception after transfer. But he did not give the solution of the model algorithm.

Summing up the results of previous studies, there is still a very long way to go in the aspects of optimization operation model and solving of the lean production system. This paper starts from the system operation state parameters, building a lean production system operation optimization model. As the operation of the production system in the market is usually a dynamic requirement, the operational status vary according to different times and different circumstances, so the solution of the model is dynamic, multi-objective and multi-stage, ‘harmonizing cluster results’ method is used to solve the model to balance and coordinate the system operation parameters continuously for get the effective optimal solution of the operation system finally. In order to verify the correctness of the model and its solution, we use Witness to simulate the applied case of the actual production of the cooperative enterprise, the results show that the model and the algorithm is reasonable and accurate.

II. ESTABLISHMENT OF THE SYSTEM OPTIMIZATION MODEL

The production system control and coordination is essentially a multi-objective, multi-stage dynamic programming problem, if we see the whole enterprise
production as a large-scale system, each unit and process of the production can be seen as a subsystem, and each subsystem is also a multi-objective, multi-stage optimization problem, these subsystems are relatively independent and linked through the enterprises. Through theoretical analysis, we can abstract these complex production system problems into a large-scale systems and multi-objective programming model with original box angular structure[3,12]. The general form is as following:

$$\min \{F(x)\}$$

$$F(x) = \begin{bmatrix} F^1 & F^2 & \cdots & F^n \\ \vdots & \vdots & \ddots & \vdots \\ F^1 & F^2 & \cdots & F^n \end{bmatrix} \begin{bmatrix} x^1 \\ \vdots \\ x^n \end{bmatrix}$$

(1)

In formula(1), m is the number of subsystems, $x^j \in X^j \subseteq R^n (j = 1, \ldots, m)$. $F^j(x^j)(j = 1, \ldots, m)$ is the objective function of sub-systems $j$, and $F(x) = (f^1(x^1), f^2(x^2), \ldots, f^n(x^n))^T$. We will discuss how to set up the a specific forms of the production control model for the complex production system:

(1) Determine the objective function

The guiding ideology of the manufacturing enterprises is to improve overall economic efficiency continuously, the main issues involved here are the multi-objective decision-making problems. These objects list as following: a. production, enterprises must meet the requirements of stable production or output orders; b. quality, enterprises must control the scrap rate or product failure rate within a certain percentage; c. costs or expenses, enterprises take profit and efficiency as the central tasks, so the economic indicators like the input and output must be controlled to a feasible extent or the cost should be as low as possible; d. delivery time, the enterprises should push their products to the market as soon as possible or complete the production tasks before the due date. Therefore, the model objective function should be able to reflect the requirements of these four aspects.

(2) Determine the decision variables

Through analysis, we assume that there are I production operators, J production machines, K raw materials, L production process species in an enterprise, the due date or the latest time the products pushed to market are T days. The decision variables in the model are: $x_{ijklm}$, production element (Staff i use method l and raw material k at machine j in the day t) workload (units: production elements), work. (i = 1, ..., I; j = 1, ..., J; l = 1, ..., L; k = 1, ..., K; t = 1, ..., T).

(3) Determine the model parameters

Although the model and decision variables can reflect the multi-target, multi-subsystem and multi-stage attributes of the production systems, it can not describe the aftereffect of the production system, that is it can’t express the differences of now and next, so it is necessary to determine the model parameters, the parameters is:

$a_{optm}$: The quality of qualified products produced in the m day by production element (Staff i use method l and raw material k at machine j in the day t) at the mth day. $m=1,2,\ldots,T$.

$b_{optm}$: The quality of defect products produced in the m day by production element (Staff i use method l and raw material k at machine j in the day t) at the mth day. $m=1,2,\ldots,T$.

$c_{optm}$: The expenses or cost of the production element (Staff i use method l and raw material k at machine j in the day t) at the mth day. $m=1,2,\ldots,T$.

(4) The specific form of the model

In the production process, the general principle of the enterprises is that the output of qualified products is as high as possible, at the same time the scrap rate and cost are as low as possible under the premise that they should guarantee the production due date. So the specific form of the model is:

$$\max \{F(x)\}$$

$$F(x) = \begin{bmatrix} \sum \sum \sum \sum a_{ijklm}x_{ijklm} \\ \sum \sum \sum \sum b_{ijklm}x_{ijklm} \\ \sum \sum \sum \sum c_{ijklm}x_{ijklm} \end{bmatrix} \begin{bmatrix} x^1 \\ \vdots \\ x^n \end{bmatrix}$$

(2)

The constraints of formula(2) are following: Constraints of the qualified products quantity, the defect products quantity, the production cost, the due date or output date are following as formula(3).

$$\sum \sum \sum \sum a_{ijklm}x_{ijklm} \geq \sum \sum a_{lm}, \sum \sum \sum \sum b_{ijklm}x_{ijklm} \leq \sum \sum b_{lm}$$

$$\sum \sum \sum \sum c_{ijklm}x_{ijklm} \leq \sum \sum c_{lm}, \sum \sum x_{ijklm} \leq X_{ijklm}$$

(3)

III. MODEL ALGORITHM

System optimization problems are usually solved by linear programming model, it is essentially considering one of the objectives as the objective function and translating the remaining objectives into restrictive conditions. This method not only ignores multi-object attributes of the real problems but also leads to size-fits consequences and even to no solution because of the rigid constraints of limitations. By adopting the goal programming model to study the large system optimization problem, we can not only reflect the multi-objective attributes of real problem but also describe the dynamic attributes of practical problems quantitatively according to the different principles in different periods by introducing the objective function priority and priority factors to reflect the important extent of many conflicting goals using the artificial intelligence.

Before we introduce this algorithm in specific, we need to understand the following two definitions and a theorem [13].

Definition 1(effective solution). Define $\hat{x} \in X$ , if no $x \in X$ can make $a \leq \hat{a}$ ( $a, \hat{a}$ are corresponding vectors of $x, \hat{x}$ respectively ) , then $\hat{x}$ is an effective solution of problem (P). We define the set of all effective solutions as
The framework of Harmonizing Cluster Results

**Definition 2** (the optimal solution). Define  \( \hat{x} \in X \), if any \( x \in X \) can make \( \hat{a} < a \), then \( \hat{x} \) is the optimal solution of problem (P). We record the set composed by all solutions of (P) as \( A_x(P) \), simply recorded as \( A(P) \),

\[
A_x(P) = \{ y \in R^k \mid y = f(x), x \in E_x(P) \},
\]

\[
A(P) = \{ y \in R^k \mid y = f(x), x \in A_x(P) \}.
\]

The relationship between the effective solutions and the optimal solution in the dictionary sense is \( E(P) = A(P) \). Theorem define \( \bar{x}^o = (\bar{x}, \bar{L}, \bar{x}^o) \in A(P^o) \) and \( \bar{x} \in A(P^j)(j = 1, 2, \ldots, m) \) then \( \bar{x}^o \in A(P) \).

Some explanation of the theorem:
1. If \( x^o \in A(P^o), x^o \in A(P^j) (j = 1, 2, \ldots, m) \) is not assure, it means that the optimal solution of the overall system may be not the optimal solution of the subsystem.
2. If \( x^o \in A(P^j) (j = 1, 2, \ldots, m) \) is not assured, it means that the optimal solution of the subsystem may be not the optimal solution of the overall system.
3. If \( x^o \in A(P), x^o \in A(P^j)(j = 0, 1, 2, \ldots, m) \) is not assured, it means that the optimal solution of the big system may be not the optimal solution of the overall system and subsystem.

The idea of ‘String-tuning’ is that first the programming problem (P) of the overall system there will be divided into \((m+1)\) sub-systems, and the objective programming model will be built. Because these problems of subsystems are of general the objective problems, the multi-stage simplex method can be used to solve them and test if it is the optimal solution for the whole system. If it is real, then the solution is the optimal solution of the original big system. Otherwise, in accordance with the information provided by the positive and negative deviations variables of all the subsystem we coordinate between the overall systems and subsystems. The framework of ‘Harmonizing Cluster Results’ is as shown in Figure 1.

**Step 1**: Solve model \( (P^j) \) \((j = 1, \ldots, m) \), define the optimal solution is \( \bar{x}^j \) and \( \bar{x} = (\bar{x}, \bar{L}, \bar{x}^o) \).

**Step 2**: Testing problem \( (P^o) \), whether the first priority is satisfied, the specific process is as follows: (1) if \( \bar{x} \) can make \( \sum f_i^j(\bar{x}) \leq b^o_i \), then go to the second priority testing. (2) If \( \sum f_i^j(\bar{x}) > b^o_i \) and \( \rho^j > 0(j = 1, \ldots, m) \), then we go to the second priority testing, and \( \rho^j > 0(j = 1, \ldots, m) \), the second priority is the test; (3) \( \sum f_i^j(\bar{x}) > b^o_i \) and there is \( j_o \in [1, 2, \ldots, m] \) which can make \( \eta^o_j > 0 \), define \( J = \{ j \mid \eta^o_j > 0, j = 1, 2, \ldots, m \} \), then go the the third step.

**Step 3**: Use the objective function value to coordinate. Coordinate the target value of problem \( (P^o) \), the value after coordination is \( \bar{b}^j \), then \( \bar{b}^j = \bar{b}^j - \sum f_i^j(\bar{x})^j \Delta \),

\[
\Delta = \sum f_i^j(\bar{x}) - b^o_i,
\]

and then go to the first step. Similarly, we coordinate the second priority level when we satisfy the first priority level, so that we can attain the optimal solution of problem (P) ultimately.

IV. APPLICATION CASE

A. Production System Model Simplification

Limited by conditions the workshop production system optimization models is simplified to attain the output optimization submodel, time optimization submodel as well as production balance and coordination submodel. The simplified model can be better applied into simulation software for the application for analysis and optimization .

1. Production system output model

Production models include the amount of input materials, products being made and the finished products, they can be obtained by the data acquisition system. Define that there are m production orders with \( Q \), in each order, then:

\[
Q = \sum Q_j = \sum \frac{Q}{\prod K_j} \quad (4)
\]

In formula (4), \( Q_j \) is the production logistics of contract \( n \) in stage \( i \), \( K_j \) is the input-output coefficients in production section \( j \), \( Q \) is the order quantity of contract \( n \). \( Q \) is the total production volume of production stage \( i \).

2. Production system time model

Time models include the time of a single garment from material input to product output, the time of each section etc. Assume that the latest delivery date of contract \( N \) is \( D_e \) and the earliest delivery date is \( D_s \), then:

\[
D_s = D_e + \sum T^j \quad (5)
\]
In formula (5), \( T \) is the production cycle of stage I, \( S \) is the number of stages from raw materials to finished products.

3. Production balance and coordinate model

Through rational and effective deployment of the production units, we make the whole production cell to achieve optimal load capacity and not surpass the production capacity. In the balance model, the main influencing factors are: the availability of raw materials, the situation of the market demand and orders, the state of equipment operations, staff efficiency etc.

\[
\min f(T_i) = \sum K_i \left| \sum_{j=1}^{n} Q_j - D_j \right| + \sum_{j=1}^{n} \frac{\sum_{i=1}^{m} Q_i}{S_i} \]

\[
\text{s.t.} \quad 90\% D_i \geq \sum_{j=1}^{n} Q_j - D_j \geq 30\% D_i
\]

\( T_v \in [d_k, d_l] \quad i = 1, 2, \ldots \quad s; \quad n = 1, 2, \ldots, m \)

In formula (6), \( T_v \) is delivery cycle of order, \( D_i \) is production capacity in production stage \( I \), \( K_i \) is adjustment factor of the production capacity load in production stage I.

B. Establishment of Simulation Model

In this paper the production of electronic energy meter is taken as an object of study. The meter is a kind of precision mechanical and electrical products and its production workshop belongs to a typical discrete processing and assembly production plant. There are 23 processes in the entire assembly line. The working serial number and the corresponding names were shown in Table I.

### Table I. Process of production line

<table>
<thead>
<tr>
<th>No.</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
<td>Plate Cut</td>
<td>Bottombase</td>
<td>Assemble</td>
<td>Powerboard Assemble</td>
<td>Assembly QC 1</td>
<td>Basicel Aging</td>
</tr>
<tr>
<td>No.</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td>10</td>
<td>11</td>
<td>12</td>
</tr>
<tr>
<td>Name</td>
<td>Displayboard Assemble</td>
<td>Signboard Assemble</td>
<td>Wipe-off dust</td>
<td>Dial Install</td>
<td>Error Adjustment</td>
<td>Insulation Inspection</td>
</tr>
<tr>
<td>No.</td>
<td>13</td>
<td>14</td>
<td>15</td>
<td>16</td>
<td>17</td>
<td>18-23</td>
</tr>
<tr>
<td>Name</td>
<td>Aging Review</td>
<td>Second check</td>
<td>Packaging</td>
<td>Sampling</td>
<td>Assembly QC 2</td>
<td>Rework 1-6</td>
</tr>
</tbody>
</table>

The Witness simulation model of the production scene of the electronic ammeter assembly plant was established in accordance with actual situation of production workshop. The assembly line was practiced in two shifts a day and 8 hours a shift. The Witness simulation model consists of 7 quality control points, 6 rework points, as well as 10 manufacturing and assembly processes points as shown in Figure 2.

In the Witness simulation model there are 23 processes. Because the production line operates two shifts each day, eight hours each shift, so the valid time a day is 57600s \((t = 3600 \times 8 \times 2 = 57600)\). Therefore, we set the running time of the model for 60000s. The following chart shows the time rate of each processing, assembly and rework processes of the model which is running 60000s (at this time 4035 products have been assembled in the production line).

![Figure 3 Time rate of each time process](image)

In the figure 3, ‘%Idle’ means the ratio of the idle time to total time in a process, ‘%Busy’ means the ratio of the busy time to the total time in a process, ‘%Block’ means the ratio of the blocked time to the total time. From the simulation results these phenomena can be found:

1. In all processes working ratios, the ratio of error adjustment, the normal aging check, second check and return work points 1-5 rework is relatively high which shows that the process is relatively busy compared with other processes. We can add some equipment and labors to balance the production lines in order to eliminate the production line bottlenecks, then balance all the work processes.

2. The board is cut too faster than the average flow rate of the entire production line, which makes that the modules processed can not smoothly move into the next process. So the lines are blocked in serious condition. The production line can be balanced by reducing the equipment and personnel input.
(3) The working rate are very low, for example, packaging, rework point 6 and sampling. The waste of manufacturing resources is very serious.

In order to meet operating requirement of the lean production system, we re-adjust the system operating state parameters by adding equipment and personnel, reducing the time of first check, error adjustment, aging check, second check and the process time of rework points 1 to 5; at the same time by reducing the equipment and personnel of packaging, sampling, rework point 6 to improve resource utilization. Through the optimization model of the production system we can attain the optimized parameters, these include: the process time of first check falls from 5s in the past to 3s; the error adjustment process time falls from 7 in the past to 4s; the process time of cutting boards is regulated from 2s in the past to 15s; the time of processes sampling batch time is adjusted from 100 s to 360 s; packaging process time is regulated from 2 to 5 s and so on, here we will not list everyone of them. After the adjusted model has run for 60000s, 5,838 products can be assembled in this production line.

From the operation results of the model after balance we can see the effect of production lines balance: (1) the output of production (running time is 60000 s) rises up to 5838 from the original 4035 and the productivity has increased by 46.8% (2) the block time ratio of module cutting board processes has decreased from 93.84% to 53.31% after the balance (3) the bottleneck processes working time is adjusted to the average time of the entire production line, reaches to the balance effect of the average level of the production lines. This shows that after the balance of the production line, the production ability of the assembly line has been significantly improved, the production line blockage has also greatly improved and the time ratio of the processes is generally the same, we have reached the requirement of balance the production.

CONCLUSION

The production process is a complex and dynamic process, the production strategy and policy in different stages is not always the same. Lean production requires the balance between the interests of the whole system and subsystems in the enterprise when the production system is operating, so that the optimal solution can be attained. “Harmonizing Cluster Results” based on the method of multi-objective optimization not only satisfies the solution of the lean production operation optimization model but also arranges the priority through the application of the electronic meter assembly line in assembly line. The priority of algorithm can be adjusted according to the production process and time situation. Through the model and algorithm simulation in Witness software, it shows that the model and its solution have high value to the improvement for the production process.

REFERENCES


