

# Condition-based maintenance optimization for multi-component systems in mass production considering customer satisfaction

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## ABSTRACT

When multiple orders with different requirements must be fulfilled under limited capacity, order selection and maintenance planning for multi-component systems become strongly interdependent. To address this problem, this study proposes a condition-based maintenance strategy for multi-component systems and a joint optimization model for multi-order batch production that incorporates customer satisfaction. First, the deterioration trend of each component is described using the proportional hazards model, and the health status of each component is represented by virtual age. Different maintenance modes are then determined according to real-time monitoring results and maintenance thresholds after the completion of each production batch. With profit maximization as the objective, the condition-based maintenance strategy is integrated with a capacitated batch production model and a customer satisfaction model to develop a joint optimization framework for maintenance and multi-order production. Finally, the model is solved using simulated annealing and particle swarm optimization. A case study is used to verify the effectiveness of the proposed approach and to demonstrate its practical relevance, and a sensitivity analysis of the key model parameters is also conducted.

## ARTICLE INFO

### Keywords:

Condition-based maintenance;  
Multi-component systems;  
Batch production;  
Maintenance optimization;  
Proportional hazards model;  
Customer satisfaction;  
Particle swarm optimization;  
Simulated annealing

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### Article history:

Received 19 January 2026

Revised 17 March 2026

Accepted 23 March 2026



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## 1. Introduction

To ensure the economic benefits of an enterprise, it is necessary to consider not only internal operational factors but also external market factors. Therefore, how to incorporate external market factors into basic production and maintenance strategies so that the enterprise can develop more effectively has become an important research focus. Traditional single-component systems have gradually evolved into multi-component systems with complex structures. Therefore, determining an appropriate maintenance method can effectively reduce costs [1]. This paper proposes a condition-based maintenance strategy model for multi-component systems based on customer satisfaction under limited production capacity.

At present, mass production is one of the most important production modes in the manufacturing industry, and there is extensive related research in this area. Huang *et al.* [2] combined the system scheduling problem, considering the completion time of batch production, with the preventive maintenance problem of a system, and built a model with completion time as the objective function. Tambe *et al.* [3] developed inspection, production, and maintenance schedules during mass production to achieve the lowest total cost per unit. Hnaien *et al.* [4] studied the mass production and preventive maintenance scheduling problem for a single machine producing multiple products and proposed a mixed-integer linear programming model with total cost as the objective function. Fitouhi *et al.* [5] combined preventive maintenance with tactical production planning and proposed a model to solve the mass production problem within a finite planning period. Lai *et al.* [6] proposed an optimal decision method for determining production lot size under a defined maintenance policy, considering imperfect manufacturing and emergency maintenance policies. Hadian *et al.* [7] considered mass production systems with stochastic degradation over time and proposed a maintenance strategy based on the predicted failure probability of each machine. Bouabid *et al.* [8] proposed an integrated production planning and preventive maintenance for manufacturing systems prone to quality degradation. Selech *et al.* [9] presented the results of reliability analysis and the corrective maintenance costs of one of the most expensive tram components to repair.

By analysing the failure mechanism and the results of equipment testing, condition-based maintenance (CBM) can avoid functional failures by repairing, adjusting, or replacing equipment when potential failures occur. Equipment can be divided into single-component systems and multi-component systems. Studies related to single-component systems have focused on the influence of external factors on maintenance decisions. Duan *et al.* [10] proposed a situational repair strategy for ship pumps under random repair quality conditions when there was a competing risk. Zhang *et al.* [11] and Zheng *et al.* [12-13] considered the impact of spare parts ordering and spare parts inventory on the development of a condition-based maintenance strategy. Zheng *et al.* [14] considered a condition-based maintenance strategy under a service performance contract. For multi-component systems, Yousefi *et al.* [15] portrayed multiple failure processes experienced by each component due to degradation and shock loading and developed models to determine the state failure thresholds and detection intervals for a multi-component system. Broek *et al.* [16] modelled system planning as a Markov decision process to study the condition-based maintenance strategy for a two-component system with economic dependence under load sharing. Wang *et al.* [17] proposed a condition-based preventive maintenance for systems with identical component equilibria. Xu *et al.* [18] used a non-homogeneous stochastic process model to emphasize the economic dependence between components and stochastic dependencies. Shi *et al.* [19] used a rolling-level method to develop a state-based maintenance decision framework for a multi-component system to meet the reliability requirements of the system.

Most research on maintenance of mass production equipment has focused on traditional corrective or periodic maintenance. As a maintenance strategy proposed in recent years, condition-based maintenance has become a preferred approach in equipment maintenance decision-making with the gradual improvement of sensing and detection technologies. However, because of its relatively short development history, few studies have applied it to mass production equipment.

Customer satisfaction has attracted extensive attention from scholars in recent years. Most of these studies quantified customer satisfaction in a specific aspect in terms of penalty cost. Liu *et al.* [20] proposed the concept of a delivery time window and constructed an early/delay penalty cost affiliation function. Iskandar *et al.* [21] considered the actual losses of port equipment and damaged parts due to maintenance overruns and transformed them into penalty costs. Nezami *et al.* [22] examined the effects of several different maintenance methods on extending equipment life and increasing satisfaction. Ruan *et al.* [23] added customer satisfaction to the total warranty cost and proposed various flexible preventive maintenance strategies.

In this paper, to address the problem of order selection and maintenance decision-making for a multi-component system when multiple orders with different requirements are placed under limited capacity, a joint optimization model of a CBM strategy for a multi-component system based on customer satisfaction and multi-order batch production is proposed. First, the specific deteriorati-

on trend of each component is described using the proportional hazards model, and the health status of each component is represented by virtual age. Then, different maintenance methods are determined according to the real-time monitoring results and maintenance thresholds after the end of each production batch. Finally, with profit maximization as the optimization goal, the CBM strategy and the joint optimization model for multi-order batch production are established by combining the limited-capacity batch problem model and the customer satisfaction model.

This study aims to develop a more effective condition-based maintenance optimization model for multi-component systems under mass production conditions. The remainder of this paper is organized as follows. The problem is described in Subsection 2.1, and a new deterioration model is developed in Subsection 2.3. Section 3 proposes a novel condition-based maintenance model for a multi-component system. Moreover, the joint optimization model of the maintenance strategy and multi-order batch production is presented in Section 4. A case study is also analysed and discussed in Section 5, and conclusions are drawn in Section 6.

## 2. Multi-component system deterioration model

Assume that within a certain period  $[0, T_x]$  (Total production time  $T_x$ ), the enterprise receives  $s$  orders with different requirements, and each order completed can obtain corresponding revenue according to the order volume. A large multi-component system in an enterprise can be produced at the rate of  $p$  pieces per day. During the production process, the components will gradually deteriorate, and the product quality will also decline. The maintenance actions will restore the status of a system, but it will also generate maintenance costs. If the repair is not timely, it will lead to frequent system failures and an increase in the unqualified rate of products, thus the order cannot be completed as required, resulting in a decrease in customer satisfaction and penalty costs, and the production and storage of products will generate corresponding production costs and inventory costs. Thus, this paper establishes a condition-based maintenance strategy model with the maximum profit of the enterprise as the optimization objective to determine the order selection and ordering, production batch size and maintenance strategy.

Consider a large multi-component production system in which each component is independent, but failure of any one component during operation causes failure of the entire system. In practice, different components fail for different reasons. For example, external parts of a system may corrode because of environmental humidity or temperature changes, whereas internal processing parts may wear because of overload operation or delayed maintenance. Therefore, before condition-based maintenance is carried out, it is necessary to consider both the failure causes and the current deterioration status of each component. Because it is difficult to combine these two aspects to construct an effective quantitative relationship, the proportional hazards model is selected to directly establish the functional relationship between the failure probability of a component and its influencing factors.

The risk function is used to describe the  $t + \Delta t, \Delta t \rightarrow 0$  probability of  $t$  failure of components  $j$  at any time without failure. Its function expression is:

$$h_j(t) = \lim_{\Delta t \rightarrow 0} P\{N_j(t + \Delta t) - N_j(t) = 1\} \tag{1}$$

where,  $N_j(t)$  represents the number of failures of component  $j$  at time  $t$ .

The function expression of the proportional risk model is:

$$h_j(t, X) = h_0(t) \cdot \exp\left(\sum_{i=1}^n \alpha_{i,j} X_{i,j}\right) \tag{2}$$

where  $X_{i,j}$  represents  $i$ -th covariate (influence factor) related to  $j$ -th component,  $\alpha_{i,j}$  is the regression coefficient corresponding to the  $i$ -th covariate, and  $h_0(t)$  is the basic risk function.

The Weibull distribution can effectively describe the deterioration law of components. If the basic risk function  $h_0(t)$  follows a Weibull distribution, substituting it into Eq. 2 yields the Weibull proportional risk model for component  $j$ :

$$h_j(t, X) = \frac{\beta}{\eta} \left(\frac{t}{\eta}\right)^{\beta-1} \exp\left(\sum_{i=1}^n \alpha_{i,j} X_{i,j}\right) \quad (3)$$

where, the shape parameters  $\beta > 1$  and scale parameters  $\eta > 1$ , as well as the covariate coefficients  $0 < \alpha < 1$  can be obtained by constructing the likelihood function, and then using the Newton-Laphson method to estimate the parameters.

### 3. Condition-based maintenance model for multi-component systems

Condition-based maintenance based on system health status is more economical and effective than single post maintenance and periodic maintenance. When formulating condition-based maintenance strategy, the degree of old and new system components should be considered, which is generally characterized by age [24]. Since the status of each component cannot be obtained in real time during the batch production process, it is necessary to detect after the batch production is completed, and determine the maintenance method in combination with the maintenance threshold. Different maintenance methods will cause the system age to fall back to different degrees, so the virtual age is introduced to more simulate the status change of each component. The current age of component  $j$  is  $A_j(t)$ , and the failure rate of component  $j$  is as follows.

$$F(A_j(t)) = \int_0^{A_j(t)} h_j(t, X) dt = \left(\frac{A_j(t)}{\eta}\right)^{\beta} \exp\left(\sum_{i=1}^n \alpha_{i,j} X_{i,j}\right) \quad (4)$$

The CBM strategy in this paper includes preventive maintenance, component replacement, minor maintenance, and opportunistic maintenance. In actual maintenance, preventive maintenance and opportunistic maintenance do not restore a component to an as-new state. The age of component  $j$  in the new state is  $A_{j,0} = 0$ , the duration of a single batch production is  $T$ , the preventive maintenance threshold is  $V$ , and the effectiveness of the  $n$ -th repair is denoted by  $\theta$ . Thus, the virtual age of component  $j$  after the end of the  $n$ -th batch production can be obtained as follows.

$$A_{j,n} = (1 - \theta)A_{j,n-1} + T \exp\left(\sum_{i=1}^n \alpha_{i,j} X_{i,j}\right) \quad (5)$$

Preventive maintenance is performed if  $A_{j,n} > V$ . Solving the above recursive relationship yields the following closed-form expression.

$$\begin{aligned} A_{j,n} &= (1 - \theta)^n A_{j,0} + \frac{1 - (1 - \theta)^n}{\theta} T \exp\left(\sum_{i=1}^n \alpha_{i,j} X_{i,j}\right) \\ &= \frac{1 - (1 - \theta)^n}{\theta} T \exp\left(\sum_{i=1}^n \alpha_{i,j} X_{i,j}\right) \end{aligned} \quad (6)$$

Because product quality is positively correlated with system deterioration, the number of defective products produced by a system increases as deterioration accelerates due to imperfect maintenance. The functional relationship between the defective rate and virtual age is given as follows:

$$p(A_n(t)) = p_0 + \mu \left(1 - \exp\left(-\lambda \left(\frac{\sum_{j=1}^l A_{j,n}(t)}{l}\right)^\gamma\right)\right) \quad (7)$$

where  $p_0$  is the initial defective rate of a system under the new condition,  $\mu$  is the boundary value of quality deterioration,  $\lambda$  and  $\gamma$  are given constants. Considering that different orders have different requirements for the defective rate, this paper sets up a quality replacement threshold  $W$  to control the product quality. When  $p(A_{j,n}(t)) > W$  after the  $n$ -th batch production is completed, the component  $j$  will be replaced and restored to a new state.

Opportunistic maintenance refers to the simultaneous repair of two components to improve maintenance economy. At the end of the  $n$ -th batch production, suppose that the virtual age of

component  $j$  is  $A_{n,j} \geq V$ , while the virtual age of component  $l$  is  $A_{n,l} < V$  and satisfies  $V - A_{n,l} \leq \Delta V$ . Here,  $\Delta V$  denotes the opportunistic maintenance threshold, and the interval  $[V - \Delta V, V]$  defines the opportunistic maintenance window. After each batch production, components that have not yet reached the preventive maintenance threshold but whose virtual ages fall within this window are repaired in advance; otherwise, they are not repaired.

During mass production, the system may shut down because of sudden failure. In this case, minor repair is performed without changing the virtual age of each component in the system and without considering maintenance time. The number of sudden failures of component  $j$  in the  $n$ -th production batch is given as follows.

$$\begin{aligned} \psi_{n,j} &= \int_0^T \frac{1 - (1 - \theta)^n}{\theta} h_{n,j}(t, X) dt = \frac{1 - (1 - \theta)^n}{\theta} \int_0^T \frac{\beta}{\eta} \left(\frac{t}{\eta}\right)^{\beta-1} \exp\left(\sum_{i=1}^n \alpha_{i,j} X_{i,j}\right) dt \\ &= \frac{1 - (1 - \theta)^n}{\theta} \cdot \exp\left(\sum_{i=1}^n \alpha_{i,j} X_{i,j}\right) \cdot \left(\frac{T}{\eta}\right)^\beta \end{aligned} \tag{8}$$

## 4. Joint optimization model of maintenance strategy and multi-order batch production

### 4.1 Capacitated lot-sizing problem (CLSP) model

The CLSP model is used to solve the problem of batch production decisions under limited capacity and resource conditions. Different mathematical models can be developed based on different influencing factors. In this paper, enterprise costs are divided into maintenance costs, production costs, and inventory costs. Accordingly, the CLSP model is defined as follows.

$$C_{CLSP} = \sum_{n=1}^N \sum_{j=1}^m MC_{n,j} + \sum_{n=1}^N (PC_n + IC_n) \tag{9}$$

$$T = T_1 = T_2 = \dots = T_n \tag{10}$$

$$\sum_{n=1}^N t_{M,n} + t_{p,n} \leq t_{total} \tag{11}$$

$$\sum_{r=1}^s O_r \leq \sum_{n=1}^N pT_n \tag{12}$$

In Eq. 9,  $1 \leq N < T_x/Q$  is the total number of production cycles, and  $m \geq 3$  denotes the number of components. Eq. 10 represents the characteristic of equal batch production time length, and  $T$  is the single batch production time length. Eq. 11 is the constraint of the total production duration under limited capacity,  $t_{M,n}$  and  $t_{p,n}$  is the maintenance duration and production duration of the  $n$ -th production cycle, respectively. Eq. 12 is the balance constraint between the total order quantity and the total capacity, and  $Q_r$  is the order quantity of  $r$ -th order.

*System maintenance cost  $MC_{n,j}$*

According to the maintenance strategy in Section 2, all components of a system are tested after the end of  $n$ -th batch production to calculate the corresponding virtual age, and compared with the preventive maintenance threshold  $V$ , component replacement threshold  $W$  and opportunity maintenance threshold  $\Delta V$  to determine the maintenance actions. The maintenance effect of opportunity maintenance is the same as that of preventive maintenance, but in a complex large system, downtime maintenance includes inspection, disassembly, and system shutdown and restart. Thus, in this paper, opportunity maintenance is defined as more economical preventive maintenance. Record the maintenance cost per unit day of preventive maintenance, component replacement and opportunity maintenance as  $mc_1, mc_2, mc_3$  and the maintenance time as  $t_{mc_1}, t_{mc_2}, t_{mc_3}$  ( $mc_3 < mc_1 < mc_2, t_{mc_1} = t_{mc_3} < t_{mc_2}$ ), respectively. The minor repair cost is  $mc_4$ , and the  $n$ -th maintenance cost for a system can be obtained.

$$MC_{n,j} = \psi_{n,j} \cdot mc_4 + \sum_{k=1}^3 mc_k \cdot t_{mc_k} \cdot \chi(A_k) \tag{13}$$

The three maintenance actions are mutually exclusive. Therefore, an indicator function  $\chi(A_k)$  is introduced in Eq. 13.

$$\chi(A_i) = \begin{cases} 1, & A_i \text{ occur} \\ 0, & A_i \text{ does not occur} \end{cases} \tag{14}$$

*Production costs PC<sub>n</sub>*

The production speed of a system is  $P$  per day, and the duration of a single batch production is  $T$  days. The production cost of a single product is denoted by  $pc$ , and the production cost of the  $n$ -th batch production is as follows.

$$PC_n = PTpc \tag{15}$$

*Inventory cost IC<sub>n</sub>*

Based on the assumptions of this paper, products currently in batch production are not included in inventory. Therefore, the inventory cost generated in the  $n$ -th batch depends on the total number of products  $I_{n-1}$  produced in the previous production cycle  $n - 1$ . The inventory cost generated during the  $n$ -th maintenance activity is related to the total number of products  $I_n = I_{n-1} + PT$  produced in  $n$  previous production. Let the inventory cost of a single product be denoted by  $ic$ . The inventory cost in the  $n$ -th production cycle is then given as follows.

$$IC_n = ic(I_{n-1}T + I_n t_{mc_k}) \tag{16}$$

If the order delivery ( $0 < t < T$ ) occurs during batch production and the order quantity is  $Q_r$ , then

$$IC_n = ic(I_{n-1}t + (I_{n-1} - O_r)(T - t) + t_{mc_k}(I_n - O_r)) \tag{17}$$

If the order delivery ( $T < t < T + t_{mc_k}$ ) occurs during the repair process, then

$$IC_n = ic(I_{n-1}T + I_n(t - T) + (I_n - O_r)(T + t_{mc_k} - t)) \tag{18}$$

**4.2 Customer satisfaction model**

In this paper, customer satisfaction is related to order delivery time and product quality. The requirement of  $r$ -th order is  $Q_r(q_r, t_r)$ , where  $Q_r$  is the order demand, and  $q_r$  and  $t_r$  are the quality and delivery time requirements, respectively. For  $t = t_r$ , if the system is in the  $n$ -th batch production stage or in the  $n$ -th maintenance stage, the product inventory  $I_n$ , the number of defective products  $DI_n$ , and the defective rate  $p$  before delivery are given as follows, respectively.

$$\begin{cases} \begin{cases} I_n(t_r)^- = I_{n-1} + pT \\ DI_n(t_r)^- = DI_{n-1} + p(A_{j,n}(T))PT \\ p_{t_r}^- = DI_n(t_r)^- / I_n(t_r)^- \end{cases} & n - \text{th batch production} \\ \begin{cases} I_n(t_r)^- = I_{n-1} \\ DI_n(t_r)^- = DI_{n-1} + p(A_{j,n}(t_r))Pt_r \\ p_{t_r}^- = DI_n(t_r)^- / I_n(t_r)^- \end{cases} & n - \text{th maintenance} \end{cases} \tag{19}$$

The remaining inventory, defective products, and defective rate after delivery can be divided into two cases: the inventory satisfies the order demand, and the inventory is insufficient.

$$\begin{cases} \begin{cases} I_n(t_r)^+ = I_n(t_r)^- - O_r \\ \begin{cases} DI_n(t_r)^+ = DI_n(t_r)^- - O_r q_r \\ p_{t_r}^+ = DI_n(t_r)^+ / I_n(t_r)^+ \end{cases} & \text{if } DI_n(t_r)^- > O_r q_r \end{cases} & \text{if } I_n(t_r)^- > O_r \\ \begin{cases} DI_n(t_r)^+ = 0 \\ p_{t_r}^+ = 0 \end{cases} & \text{if } DI_n(t_r)^- < O_r q_r \\ \begin{cases} I_n(t_r)^+ = 0 \\ DI_n(t_r)^+ = 0 \\ p_{t_r}^+ = 0 \end{cases} & \text{if } I_n(t_r)^- < O_r \end{cases} \tag{20}$$

If the quantity of products in the inventory does not meet the order demand or the defective rate is greater than the quality requirement when the delivery time arrives, the time penalty cost  $TPC_r$  and quality penalty cost  $QPC_r$  will be obtained.

$$\begin{cases} TPC_r = tpc \left( \frac{O_r - I_n(t_r)}{O_r} \right) & \text{if } I_n(t_r) < O_r \\ TPC_r = 0 & \text{if } I_n(t_r) \geq O_r \\ QPC_r = qpc \left( \frac{p_{t_r} - q_r}{q_r} \right) & \text{if } p_{t_r} > q_r \\ QPC_r = 0 & \text{if } p_{t_r} \leq q_r \end{cases} \quad (21)$$

Here,  $TPC$  and  $QPC$  are the time and quality penalty coefficients, respectively. Thus, the customer satisfaction model is as follows.

$$C_{sat} = \sum_{r=1}^s TPC_r + QPC_r \quad (22)$$

The total cost model:  $\max D = C_{CLSP} + C_{sat}$ . The revenue of an enterprise during a given period depends on the number of completed orders. Insufficient order acceptance results in idle system capacity and wasted productivity. However, accepting too many orders not only leads to high maintenance costs caused by excessive system use and deterioration, but may also prevent the enterprise from completing orders with the required quality and quantity, leading to lower customer satisfaction and even compensation. Therefore, this paper constructs a total profit model in which the batch production size  $Q$ , the preventive maintenance threshold  $V$ , the component replacement threshold  $W$ , and the opportunity maintenance threshold  $\Delta V$  are taken as decision variables. The maximum enterprise profit under different orders within the planning time period  $[0, T_x]$  is used as the overall optimization objective to determine the optimal order selection, production sequence, and corresponding decision-variable values. The income from the production of a single product is  $x$ , and the joint model is as follows.

$$\begin{aligned} \max C &= \max \left( x \sum_{r=1}^s O_r - C_{CLSP} - C_{sat} \right) \\ &= \max \left( x \sum_{r=1}^s O_r - \left( \sum_{n=1}^N \sum_{j=1}^m MC_{n,j} + \sum_{n=1}^N (PC_n + IC_n) \right) - \left( \sum_{r=1}^s TPC_r + QPC_r \right) \right) \end{aligned} \quad (23)$$

$$T = T_1 = T_2 = \dots = T_n \quad (24)$$

$$\sum_{n=1}^N t_{M,n} + t_{P,n} \leq t_{total} \quad (25)$$

$$\sum_{r=1}^s O_r \leq \sum_{n=1}^N pT_n \quad (26)$$

### 4.3 Model solving

To solve the model, it is necessary to select and sequence a given number of orders with different requirements. Therefore, the model can be regarded as a combinatorial optimization problem combining the knapsack problem and the traveling salesman problem. Considering that order selection needs to satisfy the constraints of Eq. 26, and for computational convenience and efficiency, this paper uses an enumeration method for order selection and a simulated annealing algorithm (SA) for sequencing. After the number and order of the selected orders are determined, the particle swarm optimization algorithm (PSO) is used to obtain the maximum value of the model under the given conditions. To ensure search efficiency and model convergence, the domain of the decision variables is first determined based on experience and a small number of Monte Carlo simulation results, and then a sufficient number of iterations is set to ensure that the global optimum of the model can be found. The specific algorithm steps are as follows.

Step 1. Initialize the SA parameters and PSO parameters: initial temperature  $T$ , maximum number of external iterations  $n_1$ , number of iterations at the same temperature  $n_2$ , and temperature drop rate  $\delta$ , weight coefficient  $w$ , two acceleration factors  $c_1$  and  $c_2$ , iteration times  $n_3$ , and population size  $z$ .

Step 2. Randomly select orders  $s[s_1, s_2, \dots, s_k]$  from all orders that satisfy the target function definition domain.

Step 3. Randomly generate the completion order ( $s_1 \rightarrow s_2 \rightarrow \dots \rightarrow s_k$ ).

Step 4. Randomly generate the particle population. Each particle contains four parameters: the preventive maintenance threshold  $V$ , the quality replacement threshold  $W$ , the opportunity maintenance threshold  $\Delta V$ , and the production batch size  $Q$ .

Step 5. Calculate the fitness of each particle according to the fitness function.

Step 6. Obtain the best individual fitness  $pbest$  and the best global fitness  $gbest$ .

Step 7. Update the position and velocity of each particle.

Step 8. Check whether the PSO termination conditions are satisfied. If not, return to Step 5. Otherwise, record the current global best value.

Step 9. Use the two-transformation method to change the completion order of two orders, and repeat Steps 4-7 to generate a new solution  $gbest_{new}$ .

Step 10. Calculate the increment  $\Delta = gbest_{new} - gbest$ . If  $\Delta > 0$ ,  $gbest_{new}$  is accepted as the new optimal solution; otherwise, it is accepted as the new optimal solution with probability  $p$ .

Step 11. Check whether the SA termination conditions are satisfied. If not, return to Step 9. Otherwise, record the current solution  $gbest$ .

Step 12. Reduce the temperature and repeat Steps 9-11 until the minimum temperature is reached or no new solution is generated for several consecutive iterations. Then compare all recorded solutions  $gbest$  in Step 11 and retain the maximum value.

Step 13. Return to Step 2, randomly select all possible orders again, compare all recorded values  $gbest$  from Step 12, and output the final maximum value  $gbest_{max}$ .

## 5. Case study

### 5.1 Data preparation

One enterprise receives 15 orders with different requirements within a certain period, and the estimated production time is  $T_x = 1000$  days. Through reference and analysis of the historical data of the three-component production system in a factory, the shape parameters and scale parameters are approximately  $\beta = 3.5201$ ,  $\eta = 523.254$ . The system can produce at a rate of 50 pieces/day; the unit production cost is 5 RMB/piece, and the selling price is 10 RMB/piece. The specific requirements of the order are shown in Table 1, and the cost unit price and maintenance days are shown in Table 2. Other parameters are  $\alpha_{1,1} = 0.1$ ,  $\alpha_{1,3} = 0.12$ ,  $\alpha_{1,2} = 0.11$ ,  $\theta = 0.8$ ,  $\mu = 1$ ,  $\lambda = 0.3$ ,  $\gamma = 0.5$ ,  $tpc = qpc = 10000$ , and  $ic = 0.005$ .

**Table 1** Order requirements

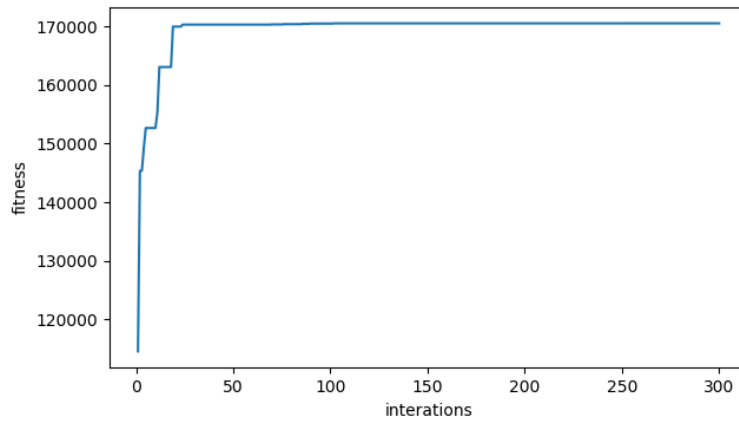
Order No	Order quantity (Piece)	Quality requirements (Defective rate)	Time requirement (Days)
1	8000	0.03	250
2	7500	0.04	230
3	5200	0.03	150
4	10000	0.04	280
5	9100	0.06	240
6	6800	0.04	220
7	8000	0.05	200
8	7700	0.03	240
9	9800	0.05	290
10	6600	0.03	230
11	9000	0.05	250
12	5900	0.06	180
13	10600	0.05	270
14	5500	0.04	100
15	11000	0.06	250

**Table 2** Maintenance costs and maintenance durations for different maintenance methods

Maintenance action	Maintenance cost	Maintenance days
Preventive maintenance	1000	3
Component replacement	3000	5
Opportunity maintenance	1000	3
Minor repair	100	0

**5.2 Result analysis**

The above parameters are substituted into the joint optimization model, which is solved using Python 3.7. The initial temperature was  $T = 100$ , the temperature drop rate was  $\delta = 0.95$ , the maximum number of external iterations was  $n_1 = 100$ , and the number of iterations at each temperature  $n_2 = 100$  in the SA process. In the PSO process, the population size was  $k = 50$ , the number of iterations was  $n_2 = 300$ , two acceleration factors were  $c_1 = c_2 = 2$ , and the inertia weight was  $w(k) = w_{start} - (w_{start} - w_{end})(T_{max} - k)/T_{max}$ . The optimal solution of the model was to produce orders in the sequence  $7 \rightarrow 13 \rightarrow 5 \rightarrow 15 \rightarrow 14$  with  $Q = 5300$ ,  $V = 112$ ,  $W = 138$ , and  $\Delta V = 8$ , which maximizes the profit of the enterprise to  $C_{max} = 170363$ . The convergence curve of the fitness function of PSO algorithm under the optimal solution is shown in Fig. 1.



**Fig. 1** Fitness function of the PSO algorithm under the optimal solution

Most optimization studies reported in the literature have used cost as the objective function. Using the same parameters, this paper also solves the optimization model with cost minimization as the objective. The optimal solution is to produce the orders in the sequence  $7 \rightarrow 4 \rightarrow 5 \rightarrow 12 \rightarrow 6$ , with  $Q = 4200$ ,  $V = 108$ ,  $W = 132$ , and  $\Delta V = 10$ , which minimizes the total cost of the enterprise to  $D_{min} = 68592$ . The optimal solutions of the two models are shown in Tables 3 and 4.

By calculation, the total cost of the enterprise under the optimal solution of the profit function is  $D_{min} = 79637$ . The total profit of the enterprise under the optimal solution of the cost function is  $C_{max} = 130408$ . These results show that using profit as the objective function increases the production batch size and maintenance threshold, thereby reducing the number of repairs within a limited time. However, this may prevent the enterprise from completing all orders as required and may therefore generate penalty costs. As a result, the cost increases by 13.8 %, but the overall enterprise income increases by 23.45 %.

**Table 3** Maintenance status under the optimal solution when profit is the objective function

Component	$mc_1$	$mc_2$	$mc_3$	$mc_4$	TPC	QPC
1	6	1	2	18		
2	5	2	2	19	1	1
3	3	3	3	21		

**Table 4** Maintenance status under the optimal solution when cost is the objective function

Component	$mc_1$	$mc_2$	$mc_3$	$mc_4$	TPC	QPC
1	7	1	3	12		
2	6	1	4	12	0	0
3	5	2	4	14		

### 5.3 Sensitivity analysis

To examine the relationship between the optimal decision variables and total enterprise profit, it is necessary to analyze the sensitivity of the optimal maintenance strategy to the maintenance cost parameters. This paper analyzes the impact of different parameter values on the optimal decision-making strategy by changing one parameter while keeping the others unchanged. Opportunity maintenance can be regarded as a special case of preventive maintenance, so no additional analysis is carried out for it. This paper considers the impact of preventive maintenance cost  $mc_1$ , component replacement cost  $mc_2$ , and minor repair costs on the optimal strategy. In general, the maintenance costs satisfy  $mc_2 > mc_1 > mc_4$ , and the parameter variation range is specified accordingly. The specific change results are shown in Table 5.

The size of batch production  $Q$  is sensitive to replacement cost  $mc_2$  and minor repair cost  $mc_4$ . When  $mc_2$  increases,  $Q$  will decrease rapidly to shorten the time of system production, reduce the number of times from system deterioration to component replacement, and reduce the maintenance cost. When  $mc_4$  increases,  $Q$  decreases in order to reduce the number of unexpected system failures and, consequently, the number of minor repairs.

Preventive maintenance threshold  $V$  and opportunistic maintenance threshold  $\Delta V$  are only slightly sensitive to preventive maintenance cost  $mc_1$ . Although  $mc_1$  varies over the same range, the actual values of  $V$  and  $\Delta V$  change only slightly. As  $mc_1$  increases, both  $V$  and  $\Delta V$  gradually increase, thereby reducing the number of preventive maintenance actions.

The component replacement threshold  $W$  is most sensitive to the component replacement cost  $mc_2$  and is also sensitive to  $mc_1$  and the minor repair cost  $mc_4$ . When  $mc_1$  or  $mc_4$  increases, the value of  $W$  decreases, accelerating component replacement and reducing the number of preventive maintenance actions and minor repairs. When  $mc_2$  increases, the value of  $W$  increases significantly, making the components more inclined toward the more economical preventive maintenance strategy.

Total profit  $C$  is the most sensitive to the replacement cost  $mc_2$ , followed by preventive maintenance cost  $mc_1$ , and the least sensitive is minor repair cost  $mc_4$ . Due to  $mc_2 > mc_1 > mc_4$ , the effect of component replacement is better than preventive maintenance. If the two values are similar, the maintenance strategy becomes more inclined toward increasing the number of component replacements; conversely, more preventive maintenance will be adopted.

**Table 5** Results of the sensitivity analysis

Parameter	Range of variation (%)	$Q$	$V$	$W$	$\Delta V$	$C$
$mc_1$	\	5300	112	138	8	170363
	-50	5100	110	141	9	181251
	-25	5300	111	140	8	176489
	+25	5400	112	137	7	165334
	+50	5400	114	136	7	159641
$mc_2$	-50	5800	111	131	8	188343
	-25	5600	112	134	8	181376
	+25	5000	112	142	7	162373
	+50	4800	113	147	8	151335
$mc_4$	-50	5600	113	140	8	178131
	-25	5400	113	139	7	173164
	+25	5100	112	138	7	168779
	+50	5000	111	136	7	163498

## 6. Conclusion

This paper proposes a condition-based maintenance strategy model based on customer satisfaction. In the modeling process, the limited production time is divided into multiple production cycles of equal length, and the maintenance action after each cycle is determined based on the deterioration of each component in the system and the maintenance thresholds. The limited-capacity batch problem model is formed by combining the maintenance, inventory, and production costs generated during enterprise operation with the production constraints, after which the order

requirements are compared with the actual delivery performance. If the order requirements are not met, corresponding penalty costs are incurred, thereby forming the customer satisfaction model. This paper integrates the batch production problem under limited capacity, the customer satisfaction problem in order delivery, and the condition-based maintenance strategy, and takes the maximization of enterprise profit as the optimization objective. An optimal condition-based maintenance strategy model is established, and its effectiveness is verified through a case study.

## Acknowledgement

The work presented in this paper was supported by the National Natural Science Foundation of China (No. 72271161).

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