Multi-Objective Production Cost Control and Strategy Optimization Using Whale Optimization Algorithm

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Abstract. As competition in the global electronics manufacturing industry intensifies and market demands evolve, enterprises face the urgent challenge of minimizing production costs while ensuring product quality, and enhancing their competitiveness. This paper focuses on the issue of defective rates in spare parts 1, spare parts 2, and finished products during the electronics production process. It constructs a comprehensive optimization model for production testing and disassembling. The objective is to help enterprises maximize profits and reduce production costs by optimizing testing and disassembling strategies for spare parts and finished products and managing unqualified products effectively through disassembling or discarding. In this paper, we propose the following hypotheses: the probability of spare part i being tested is denoted as P_i, the probability of a finished product being tested is denoted as P, and the disassembly rate of unqualified products is denoted as θ. Utilizing the Whale Optimization Algorithm (WOA), this paper establishes a multi-objective optimization model to seek the optimal strategy in the production process. Our findings indicate that, in scenario 4, testing spare parts and finished products but not disassembling unqualified finished products yields the optimal solution. The total expected cost under this strategy is approximately 29.99 yuan.

Keywords: Whale Optimization Algorithm, Multi-objective Optimization Model, Cost Minimization, Enterprise Production Decision-making.

1. Introduction

In recent years, with the intensification of global manufacturing competition and the constant evolution of market demands, enterprises have faced increasing challenges in their production processes [1]. Among these, minimizing production costs while ensuring product quality has become a core concern for enterprises [2]. Traditional quality control methods have largely focused on optimizing single production stages, neglecting the interdependencies and correlations among various stages of the multi-stage production process. Especially in cases involving unqualified products, different testing, and disassembling strategies can directly impact an enterprise's overall costs and operational efficiency.

This paper applies the Whale Optimization Algorithm (WOA) to the production processes of enterprises, leveraging intelligent algorithms to find optimal strategies [3-5]. Specifically: First, the enterprise's production process is analyzed, and a production flowchart is drawn to facilitate subsequent research. Then, reasonable hypotheses are proposed to analyze the various costs involved in the production of electronic components, with corresponding calculation formulas provided. Additionally, considering the possibility of cyclical processes arising during production, the single-cycle scenario is incorporated into the analysis. Next, the objective function of the optimization model is formulated by comprehensively considering enterprise costs, revenues, and reputation. Finally, the WOA is employed to solve the objective function, and the data is visualized to conclude. Cost Minimization Strategies for Part Inspection and Disassembly.

2. Cost Minimization Strategies for Part Inspection and Disassembly

2.1. Scenario Analysis

This study utilizes data sourced from https://www.mcm.edu.cn/. Here, we establish a scenario where a company intends to assemble Spare parts 1 and 2 into Finished products. If either spare part is unqualified, the finished product will inevitably be unqualified. The company has the option to test Spare parts 1 and 2 to determine their quality. Even if both spare parts are qualified, the assembled finished product may still be unqualified. Before selling the finished product, the company can choose to test it or sell it directly to the customer. If the customer receives an Unqualified Product, the company will need to pay a return and exchange fee. For Unqualified Products, the company can either scrap them or disassemble them. The disassembly process will not damage the spare parts but will incur disassembly costs. This production process comprises six situations, involving parameters such as the defective rate α, purchase price per unit X, testing cost Q, selling price of the finished product P, exchange cost S, and disassembly cost H. A summary of these scenarios is provided in Table 1:

Table 1. Summary of Production Process Situations

Situation	Spare parts 1			Spare parts 2			Finished products				Unqualified Product	
	α	X	Q	α	X	Q	α	X	Q	P	S	H
1	10%	4	2	10%	18	3	10%	6	3	56	6	5
2	20%	4	2	20%	18	3	20%	6	3	56	6	5
3	10%	4	2	10%	18	3	10%	6	3	56	30	5
4	20%	4	1	20%	18	1	20%	6	2	56	30	5
5	10%	4	8	20%	18	1	10%	6	2	56	10	5
6	5%	4	2	5%	18	3	5%	6	3	56	10	40

By analyzing the aforementioned production process, can be broadly divided into the spare part testing stage (Figure 1) and the finished product testing stage (Figure 2), which are presented in the form of flowcharts as follows:

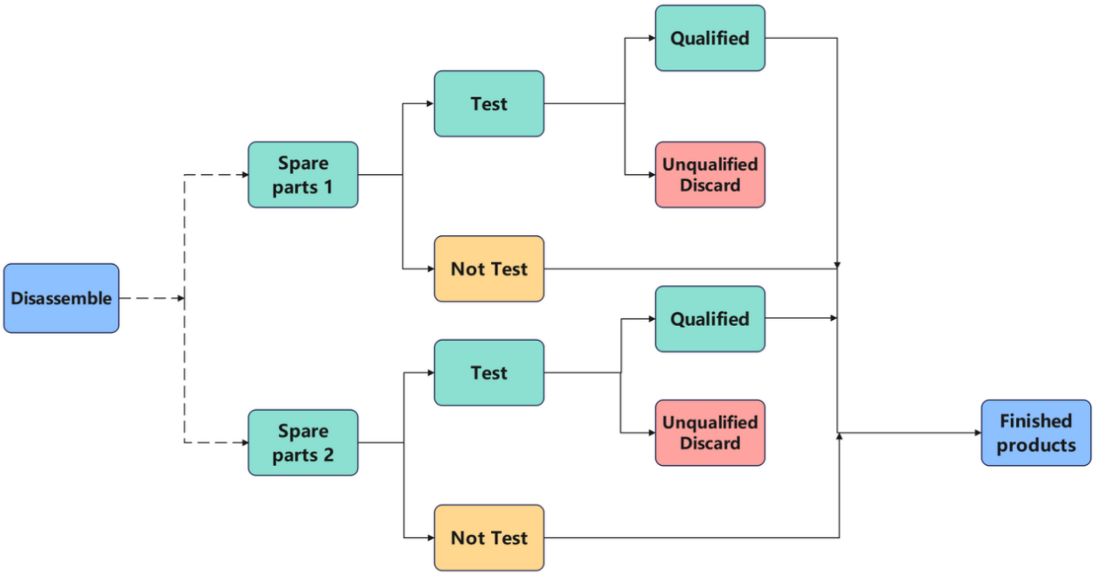

Figure 1. Flowchart for the Spare Part Testing Stage

In the spare part testing stage, both spare parts 1 and 2 can either be procured or sourced from product disassembly (indicated by dashed lines). If the spare parts are tested, those that pass the test are used for assembling the finished product, while those that fail are discarded. If the spare parts are not tested, they are directly used for assembling the finished product.

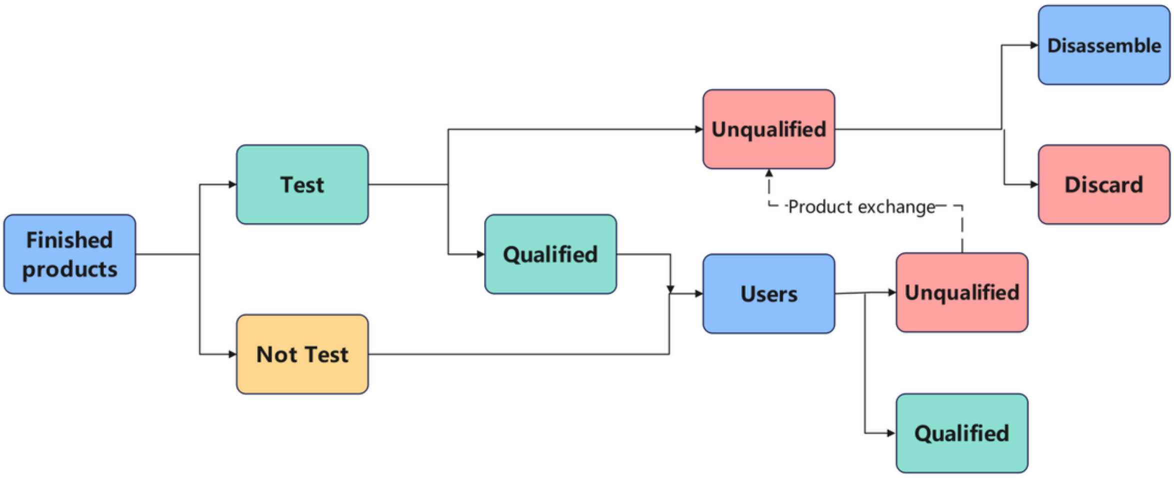

Figure 2. Finished Product Testing Stage

In the finished product testing stage, the two spare parts have already been assembled into a finished product. At this point, there is an option to test the finished product. If the finished product is tested and passed, it will be sold to the user. If the finished product is not tested, it will be directly sold to the user. However, if the user receives a defective product, it will be returned to the company through a product exchange process. During the finished product testing process, defective products can be discarded or dismantled. Since dismantling the product does not damage the spare parts, the spare parts 1 and 2 generated from dismantling will return to the spare part testing stage, thus creating a cycle.

2.2. Preliminary calculation

2.2.1. Cost calculations

After analysis, the main sources of production costs for the enterprise are as follows: spare part purchase costs (c_1), spare part testing costs (c_2), finished product assembly costs (c_3), finished product testing costs (c_4), costs associated with exchanging defective products (c_5), and costs associated with dismantling defective products (c_6). In this paper, we propose the following hypotheses:

(1) The probability of spare part i being tested is denoted as P_i, the probability of a finished product being tested is denoted as P, and the disassembly rate of unqualified products is denoted as θ.

(2) Assume that the defect rates among different components and the defect rate of finished products are mutually independent.

(3) Assume that components participate in the cycle at most once. In the actual production process, the probability of components participating in two or more cycles is relatively small, and the impact on the total cost is minor and can be neglected. We believe that considering one cycle is sufficient to reflect the recyclable characteristics of the model.

(4) Assume that all products produced by the enterprise are sold.

1) Spare part purchase costs $\mathbf{c_1}$

The purchase costs of spare parts depend on the unit prices and purchase quantities of spare parts 1 and 2, which can be represented by Formula 1:

$$c_1 = \sum_{i=1}^{2} N_i x_i \tag{1}$$

Where: N_i represents the quantity of the ith type of spare part purchased, and x_i represents the unit price of the ith type of spare part.

2) Spare part testing costs $\mathbf{c_2}$

The costs of spare part testing depend on the testing fee per part and the number of parts being tested, which can be represented by Formula 2:

$$c_2 = \sum_{i=1}^{2} N_i q_i P_i \tag{2}$$

Where: q_i represents the testing costs per unit of the ith type of spare part, and P_i represents the probability that the ith spare part will be tested.

3) Finished product assembly costs $\mathbf{c_3}$

The assembly costs of spare parts arise from the parts that have passed inspection and those that have not been tested. Since the finished product assembly costs depend on the quantity of finished products, the smaller value between the quantities of spare parts 1 and 2 used for assembly is taken as D:

$$D = \min_{1 \le i \le n} \left\{ N_i P_i \left(1 - \alpha_i\right) + N_i \left(1 - P_i\right) \right\} \tag{3}$$

Where: a_i represents the defect rate of the ith type of part, and D represents the number of finished products produced through assembly.

Therefore, the finished product assembly costs can be represented by Formula 4:

$$c_3 = D \cdot M \tag{4}$$

Where: M represents the assembly costs per unit product.

4) Costs associated with exchanging defective products $\mathbf{c_4}$

Similarly, the finished product testing costs are determined by the number of finished products that undergo inspection and the inspection cost per unit product, as shown in Formula 5:

$$c_4 = D \cdot P \cdot Q \tag{5}$$

Where: P represents the probability of finished product inspection, and Q represents the inspection cost per unit product.

5) Costs associated with exchanging defective products $\mathbf{c_5}$

The costs of replacing defective products arise from the defective products within the finished products that have not been tested. Based on the assumptions of this model: the defect rates α_i among different components and the defect rate α_0 of the finished products are mutually independent. Therefore, according to the principle of inclusion and exclusion, the total defect rate α of the finished products before testing can be calculated as follows:

$$\alpha = \sum_{i=0}^{2} \alpha_i - \alpha_0\alpha_1 - \alpha_0\alpha_2 - \alpha_1\alpha_2 + \alpha_1\alpha_2\alpha_3 \tag{6}$$

Based on this, we can derive the formula for calculating the costs of replacing defective products:

$$c_5 = D \cdot (1 - P) \; S\alpha \tag{7}$$

Where: S represents the replacement cost per user.

6) Costs associated with dismantling defective products $\mathbf{c_6}$

Regarding the disassembly cost of defective products, this indicator depends on the number of defective products and the disassembly rate ε. The number of defective products has two sources: one is the defective products returned by users, and the other is the defective products discovered during the finished product inspection process. The number of defective products can be represented by formula 8:

$$D \cdot P \cdot \alpha + D \cdot \left(1 - P\right) \cdot \alpha = D \cdot \alpha \tag{8}$$

From this, we can obtain the disassembly cost of the products:

$$c_6 = D \cdot \alpha \cdot \varepsilon \cdot H \tag{9}$$

Where: H represents the disassembly cost per unit product.

However, since the dismantled spare parts 1 and 2 are returned to the assembly stage, they will incur new related costs. Let's denote the number of ith type of parts dismantled during the (j-1) th disassembly as N_i^j, which incurs spare part purchase costs (c_1), spare part testing costs (c_2), finished product assembly costs (c_3), finished product testing costs (c_4), but does not incur spare part purchase costs (c_1). In this paper, it is assumed that the dismantled parts will not be dismantled again, meaning that the cycle occurs at most once and no further costs associated with dismantling defective products (c_6) will be incurred.

Let's denote the additional costs arising from the dismantled parts as follows: spare part testing costs, finished product assembly costs, finished product testing costs, and costs associated with exchanging defective products, which are represented as c_2^1, c_3^1, c_4^1, c_5^1.

Based on the formula derivations in the previous sections, for c_i^1, when i=2,3,4,5, we only need to replace the part quantity N_i with N_i^1 to obtain the c_i^1 calculation formula:

$$\begin{cases} c_2^1 = \sum_{i=1}^{2} N_i^1 q_i P_i \\ D^1 = \min_{1 \le i \le n} \left\{ N_i^1 P_i \left(1-\alpha_i\right) + N_i^1 \left(1-P_i\right) \right\} \\ c_3^1 = D^1 M \\ c_4^1 = D^1 PQ \\ c_5 = D^1 (1-P) S\alpha \end{cases} \tag{10}$$

Where: D^1 represents the number of finished products formed by the assembly of spare parts after the first round of disassembly. From this, we can derive the calculation formula for the total cost C_o of the enterprise, which is formula 11:

$$C_0 = \sum_{i=1}^{6} c_i + \sum_{i=2}^{5} c_i^1 \tag{11}$$

2.2.2. Income calculation

For enterprises, revenue originates from the volume of user purchases. In this article, it is assumed that all products produced by the enterprise are sold, so it is only necessary to calculate the quantity of products purchased by users. Under this assumption, the products purchased by users also come from two sources: finished products that are qualified without disassembly and finished products that are qualified after one disassembly, with their quantities represented by Equation 12:

$$\begin{cases} Num = DP(1-\alpha) + D(1-P)\alpha \\ Num^1 = D^1 P(1-\alpha) + D^1(1-P)\alpha \end{cases} \tag{12}$$

Where: Num represents the quantity of finished products that are qualified without disassembly, and Num^1 represents the quantity of finished products that are qualified after one disassembly.

From this, we can derive the total revenue E_o of the enterprise and the total profit R_o of the enterprise:

$$E_o = \left(Num + Num^1\right) \cdot e \tag{13}$$

$$R_o = E_o - C_o \tag{14}$$

Where: e represents the unit price of the finished products.

3. Application of Whale Optimization Algorithm in Cost Optimization

3.1. Model Building

3.1.1. Decision variables

The decision variables for the optimization model are selected from those that influence the calculations of cost and revenue. Based on the assumptions in this article, the probability P_i of component i being inspected, the probability P of finished products being inspected, and the disassembly rate ε of non-conforming products are chosen as the decision variables.

3.1.2. Restraint condition

The probability P_i of component i being inspected, the probability P of finished products being inspected, and the disassembly rate θ of non-conforming products should all be restricted between 0 and 1.

$$\begin{cases} 0 \le P_i \le 1 \\ 0 \le P \le 1 \\ 0 \le \varepsilon \le 1 \end{cases} \tag{15}$$

3.1.3. Objective function

In the actual production process, from the perspective of short-term profitability for the enterprise, it is necessary to minimize total costs C_o and maximize profits R_o. From the perspective of long-term profitability, it is essential to maintain a good corporate reputation, thus minimizing the return of non-conforming products, i.e., minimizing Costs associated with exchanging defective products c_5. Therefore, the objective function is set as follows:

$$\min F = (-R_o, C_o, c_5) \tag{16}$$

3.2. Whale Optimization Algorithm

3.2.1. Algorithm principle

The Whale Optimization Algorithm (WOA) is a heuristic intelligent optimization algorithm inspired by the behavior of whale populations. It achieves its exploration and exploitation by simulating the foraging behavior of whales, primarily consisting of three phases: Encircle Prey, Bubble-net Attack, and Search for Prey [6-7].

3.2.2. Algorithm flow

Because of its outstanding performance, WOA is widely applied in different fields, characterized by simple operation, a small number of parameters to adjust, abundant integrated mechanisms, and a strong capability to escape local optima [8]. The algorithmic flow of WOA is presented in Table 2.

Table 2. The algorithmic flow of WOA

Step	Operate	Explain
Step1	Initialize Population	Randomly generate a certain number of initial individuals to serve as the starting solutions for the population.
Step2	Evaluate Fitness	Assess each individual in the population using a fitness function, providing a corresponding fitness value.
Step3	Selection Operation	Use a selection operator to choose a portion of individuals from the current population to serve as parents for generating the next generation.
Step4	Crossover Operation	Apply a crossover operator to the selected parent individuals to generate new offspring individuals.
Step5	Mutation Operation	Perform mutation on the generated offspring individuals to increase population diversity.
Step6	Evaluate Fitness	Evaluate the newly generated offspring individuals using the fitness function.
Step7	Environmental Selection	Utilize an environmental selection operator to choose a subset of individuals from both the current population and the newly generated offspring to form the next generation.
Step8	Termination Condition	Determine whether the termination condition is met. If not, return to Step 3; otherwise, terminate the algorithm.
Step9	Output Results	Output the optimal solution or the optimal individual.

4. Conclusion

By utilizing WOA, the calculation results are presented in Table 3.

Table 3. Summary of Results for Six Situations

Situation	Spare parts 1	Spare parts 2	Finished products	Unqualified Product	Total expected cost/yuan
1	Test	Test	Not Test	Disassemble	30
2	Test	Test	Not Test	Disassemble	30
3	Test	Test	Not Test	Disassemble	30
4	Test	Test	Not Test	Disassemble	26
5	Not Test	Test	Test	Disassemble	30
6	Test	Not Test	Not Test	Not Disassemble	27

For situations 1 to 4, both spare parts 1 and spare parts 2 are tested, while finished products are not tested. Unqualified products are disassembled for disposal. In situation 5, spare parts 1 are not tested, but spare parts 2 are tested, and finished products are also tested. Unqualified products are disassembled. In situation 6, spare parts 1 are tested, but spare parts 2 are not, and finished products are not tested either. Unqualified products are not discarded in this case. In summary, when the cost of testing spare parts is low, testing both components can help save costs. In the initial stages of industrial production, conducting good quality tests can minimize the high dismantling costs and replacement losses in the later stages, prevent damage to corporate reputation, and often maximize profits for the enterprise.

In the context of quality control for electronic product manufacturing enterprises, this paper establishes a comprehensive production testing and disassembly optimization model. The aim is to assist enterprises in reducing production costs and increasing overall profits by optimizing testing and disassembly strategies. The model developed in this paper comprehensively considers key factors in multiple production stages, including the defect rates of spare parts and finished products, testing costs, disassembly costs, and replacement losses. Therefore, it provides important reference and practical significance for production decision-making in real-life enterprises [9-10].

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