Research on Decision-making Method for Allocation of Product Maintenance Spare Parts

Wu Qian¹, a, Wang Chaowei², Pei Fei³, b*, Xu Yingcheng¹ and Lu Xiaowei¹

¹China National Institute of Standardization, Beijing, China
²China Ship Develop and Design Center, Wuhan, China
³China standard promoting quality science and technology (Beijing) co., ltd, Beijing, China

Corresponding author: a*ustbwuqian@163.com; b*Peifei@cnis.ac.cn

Abstract. Under the current market situation, improving the efficiency and quality of after-sales service has become one of the effective means for improving the competitiveness of an enterprise. In this paper, the cost coefficient method is introduced into the research on decision-making method for allocation of product maintenance spare parts. By analyzing the factors influencing the transportation of maintenance spare parts, a model is established for the allocation cost coefficient of maintenance spare parts. The optimal transportation route of maintenance spare parts is calculated by using A-star algorithm. The optimal allocation scheme is obtained according to the table-manipulation method on linear programming. The feasibility of the model is verified by an example. The method is scientific, reasonable, simple and easy to learn. With strong generalization and operability, the method can effectively improve the allocation efficiency of maintenance spare parts and save the cost of after-sales service.

1. Introduction

With more and more fierce market competition, improving the efficiency and quality of after-sales service has become one of the effective means for improving the competitiveness of an enterprise. However, the higher the standard for after-sales service is and the faster the response speed is, the higher the cost of after-sales service is[1]. Warehouse site selection, inventory and transportation of product maintenance spare parts and so on belong to the main costs of after-sales service for an enterprise. If sufficient maintenance spare parts can be effectively delivered to various maintenance sites in a timely manner, an enterprise is able to reduce service costs and increase profits while maintaining high service satisfaction. Therefore, improving the transportation efficiency and optimizing the inventory of maintenance spare parts and the warehouse site selection are one of the effective ways to ensure the healthy and sustainable development of an enterprise.

At present, domestic and foreign scholars carried out a series of researches on spare parts storage, transportation, allocation, warehouse site selection, etc., and also achieved certain research results. Yu Hang (2015)[2], Xia Yunfei (2015)[3], Guo Sen (2016)[4], et. al. turned the issue on multi-echelon servicing inventory optimization of repairable spare parts into the issue on multi-objective optimization. A multi-objective parameter optimization model was established to optimize the spare parts inventory and transportation route. Hou Duoli (2019)[5], Lv You (2019)[6], Wu Jiajia (2018)[7], Wy J(2012)[8], et. al. introduced the genetic algorithm, bat algorithm, time window constraint, etc. into the research on optimization of spare parts scheduling route, which enhances the efficiency of
spare parts supply scheduling between sites at different servicing levels. Jin Yangfei (2018)[9], Wang Jing (2014)[10], Zeng Wenliang (2014)[11], et. al. proposed the EIQ-ABC method to optimize the storage and sorting mode of spare parts warehouse by analyzing customer order data and planning the storage location and sorting mode of spare parts.

It was found in the above research results that present researches developed by domestic and foreign scholars for spare parts scheduling and transportation mostly focused on large-scale equipment such as weapons, ships and automobiles. The established decision-making model and algorithm model are relatively large and complex, which are not easy to popularize for common products and common manufacturers. Therefore, on the basis of combining the existing research results and practical needs, this paper introduces the concept of cost coefficient into decision-making for spare parts allocation, in order to build a more convenient, easy-to-use and scientific optimization model for spare parts allocation and transportation, which provides a method support for improving the allocation of product maintenance spare parts by an enterprise.

2. Influencing Factors of Spare Parts Allocation and Transportation Efficiency
Timeliness, reliability and economy are important indicators for evaluating transportation efficiency [12]. Therefore, as for the analysis of influencing factors of spare parts allocation and transportation, the above three factors should be emphatically analyzed.

2.1. Analysis of Influencing Factors

2.1.1. Timeliness. The timeliness factors that affect the allocation and transportation efficiency of product maintenance spare parts mainly include the preparation time for spare parts packaging, loading and unloading and so on before transportation, the waiting time for vehicles to leave the warehouse and for issuance of transportation allocation instructions and so on before transportation, and the delivery time during transportation. The sum of the preparation time, waiting time, and delivery time is called the transportation time, expressed as $T$.

2.1.2. Reliability. Reliability refers to the possibility of completing the task of transporting maintenance spare parts from the warehouse to the maintenance site under specific transportation environment and conditions. It is expressed by the probability $P$ of delivering the maintenance spare parts safely to the destination through the transportation route.

2.1.3. Economy. Economy refers to the sum of all costs for personnel, equipment, energy consumption and transportation incurred in the delivery of maintenance spare parts, expressed by transportation charge $C$.

2.2. Expression of Influencing Factors

Assuming: The maintenance servicing spare parts warehouse is expressed as $A_i$ (where: $i = 1, 2, 3, \ldots, m$); the spare parts storage quantity in each warehouse is expressed as $a_i$ (where: $i = 1, 2, 3, \ldots, m$); the product maintenance servicing site is expressed as $B_j$ (where: $j = 1, 2, 3, \ldots, n$); the spare parts demand of each warehouse is expressed as $b_j$ (where: $j = 1, 2, 3, \ldots, n$); the spare parts inventory of the maintenance servicing spare parts warehouse is sufficient and expressed as $\sum_{i=1}^{m} a_i > \sum_{j=1}^{n} b_j$ (which means the supply exceeding the demand).

Then: In the process of transporting the maintenance spare parts from the warehouse to the maintenance site, the transportation route between any two connected sites $A_i$ and $B_j$ is expressed as $L_{A_i, B_j}$; the transportation time $T_{A_i, B_j}$, safe arrival probability $P_{A_i, B_j}$ and transportation charge $C_{A_i, B_j}$ consumed between any two sites are called the transportation cost. The weight of transportation cost is obtained according to the actual demand, expert judgment, etc. The arithmetic product of the weight of
transportation cost and the standardized transportation cost matrix is called transportation cost coefficient. The cost coefficient between any two connected sites is expressed as $K_{A_iB_j}$.

3. Optimization Model for Spare Parts Allocation and Transportation

3.1. Determination of Cost Coefficient

3.1.1. Transportation Route Matrixing. The transportation route between any two connected sites $A_i$ and $B_j$ is expressed as $L_{A_iB_j}$; the transportation time spent on the connected route is expressed as column vector $T$; the safe arrival probability is expressed as column vector $P$; the transportation charge is expressed as column vector $C$. The column vectors $T$, $P$ and $C$ form a transportation route matrix, expressed as $Q$, as follows:

$$ Q = \begin{bmatrix} T_{A_1B_1} & P_{A_1B_1} & C_{A_1B_1} \\ T_{A_1B_2} & P_{A_1B_2} & C_{A_1B_2} \\ \vdots & \vdots & \vdots \\ T_{A_iB_j} & P_{A_iB_j} & C_{A_iB_j} \end{bmatrix} $$

(1)

Where:
- $T = \begin{bmatrix} T_{A_1B_1}, T_{A_1B_2}, \ldots, T_{A_iB_j} \end{bmatrix}^T$, $A_i$ and $B_j$ refer to any two connected sites; $i$ and $j$ refer to the subscripts of expressions for such sites;
- $P = \begin{bmatrix} P_{A_1B_1}, P_{A_1B_2}, \ldots, P_{A_iB_j} \end{bmatrix}^T$, $A_i$ and $B_j$ refer to any two connected sites; $i$ and $j$ refer to the subscripts of expressions for such sites;
- $C = \begin{bmatrix} C_{A_1B_1}, C_{A_1B_2}, \ldots, C_{A_iB_j} \end{bmatrix}^T$, $A_i$ and $B_j$ refer to any two connected sites; $i$ and $j$ refer to the subscripts of expressions for such sites.

3.1.2. Normalization of Transportation Matrix. In order to eliminate the problems caused by dimension differences among transportation time, safe arrival probability and transportation charge, the transportation matrix $Q$ needs to be normalized. Because of the safe arrival probability $P_{A_iB_j} \in [0,1]$, the column vector $P$ needs not to be normalized.

Set $t = \max \left\{ T_{A_iB_j} \right\}$ and $c = \max \left\{ C_{A_iB_j} \right\}$, normalize the column vectors $T$ and $C$ of the matrix $Q$ to obtain the normalized transportation matrix $\bar{Q}$, expressed as:

$$ \bar{Q} = \begin{bmatrix} \frac{T_{A_1B_1}}{t} & \frac{P_{A_1B_1}}{c} & \frac{C_{A_1B_1}}{c} \\ \frac{T_{A_1B_2}}{t} & \frac{P_{A_1B_2}}{c} & \frac{C_{A_1B_2}}{c} \\ \vdots & \vdots & \vdots \\ \frac{T_{A_iB_j}}{t} & \frac{P_{A_iB_j}}{c} & \frac{C_{A_iB_j}}{c} \end{bmatrix} $$

(2)

3.1.3. Standardization of Transportation Matrix. In order to reduce the after-sales service cost for maintenance, the allocation route of maintenance spare parts should ensure the least transportation time, the highest safe arrival probability and the lowest transportation charge. As the transportation time and transportation charge are cost indicators, and the safe arrival probability is benefit indicator, in order to ensure the consistency of indicators, the indicator of safe arrival probability should be converted into a cost indicator. The standardized matrix is expressed as $Q'$:
\[
\bar{Q}' = \begin{bmatrix}
T_{A1B1} & T_{A1B2} & \cdots & T_{A1Bn} \\
\frac{P_{A1B1}}{c} & \frac{P_{A1B2}}{c} & \cdots & \frac{P_{A1Bn}}{c}
\end{bmatrix}
\]  

(3)

Where: \( P_{A1Bj} = 1 - P_{A1Bj} \).

3.1.4. Determination of the Weight of Transportation Cost. The transportation time, safe arrival probability and transportation charge are the transportation cost for transporting the maintenance spare parts from the warehouse to the maintenance site. Their weight coefficients can be obtained according to actual needs by means of experts grading method, AHP method, Delphi method, etc. The weight coefficient matrix \( W \) is calculated as follows:

\[
W = (W_T, W_P, W_C)
\]  

(4)

Where:

- \( W_T \) refers to the weight of transportation time,
- \( W_P \) refers to the weight of safe arrival probability,
- \( W_C \) refers to the weight of transportation charge.

3.1.5. Calculation of Cost Coefficient. In the process of allocating maintenance spare parts, the cost coefficient between any two connected sites is expressed as \( K_{A1Bj} \), and the cost coefficient matrix \( K \) is calculated as follows:

\[
K = W\bar{Q}'T = (W_T, W_P, W_C) \begin{bmatrix}
T_{A1B1} & P_{A1B1} & C_{A1B1} \\
T_{A1B2} & P_{A1B2} & C_{A1B2} \\
\cdots & \cdots & \cdots \\
T_{A1Bn} & P_{A1Bn} & C_{A1Bn}
\end{bmatrix}^T
\]  

(5)

3.2. Determination of the Optimal Transportation Route

After the cost coefficient is calculated, the issue on the optimal transportation route for maintenance spare parts is turned into the issue on solving the route with minimum cost coefficient. The transportation route between the warehouse and the maintenance site is simplified according to the cost coefficient, and an effective route exploration algorithm (such as A-star algorithm) [13] is adopted to solve the route with minimum cost coefficient between the warehouse and the maintenance site. Such a route is the optimal transportation route for maintenance spare parts.

3.3. Determination of the Optimal Allocation Scheme

3.3.1. Table for Supply and Demand of Spare Parts at Minimum Cost. According to the optimal transportation route between the warehouse and the maintenance site calculated above and the minimum cost coefficient on this route, as well as the known spare parts storage quantity and demand of each warehouse and maintenance site, the table for supply and demand of maintenance spare parts at minimum cost is formulated to define the minimum cost coefficient and the spare parts supply and demand relationship of each warehouse and maintenance site. The specific structure is shown in Table 1 below:

**Table 1. Supply and Demand of Maintenance Spare Parts at Minimum Cost**

| Warehouse | Maintenance Site | \( B_1 \) | \( B_2 \) | \( \ldots \) | \( B_n \) | Storage Quantity |
|-----------|------------------|-----------|-----------|-------------|-------------|-----------------|
| \( A_1 \) | \( K_{A1B1} \)   | \( K_{A1B2} \) | \( \ldots \) | \( K_{A1Bn} \) | \( a_1 \)       |                 |
| \( A_2 \) | \( K_{A2B1} \)   | \( K_{A2B2} \) | \( \ldots \) | \( K_{A2Bn} \) | \( a_2 \)       |                 |
| \( \ldots \) | \( \ldots \)     | \( \ldots \) | \( \ldots \) | \( \ldots \)    | \( \ldots \)   |                 |
3.3.2. Calculation of the Optimal Allocation Scheme. Based on the Table for Supply and Demand of Maintenance Spare Parts at Minimum Cost, the initial solution for the transportation scheme of maintenance spare parts is calculated according to the minimum element method of the table-manipulation method on linear programming, and the corresponding test numbers are obtained by using the potential method. By observing that all the test numbers are not less than zero, the initial solution can be considered as the optimal allocation scheme.

4. Case Analysis

4.1. Case Background
A household appliance manufacturer sets up three maintenance spare parts warehouses in North China. Three after-sales maintenance sites far away from the warehouses are in urgent need of a maintenance spare part. The manufacturer's after-sales service department works out an emergency transportation route, with known storage quantity and demand of maintenance spare parts, as well as transportation time, safe arrival probability and transportation charge between any two connected sites, as shown in Figure 1 below.

![Figure 1. Schematic Diagram for Transportation Route of Maintenance Spare Partt](image)

4.2. Case Model Solution
The transportation route is shown in Figure 1. According to Equation (1), the schematic diagram for the transportation route can be converted into the transportation route matrix $Q$, expressed as follows:

$$
Q = \begin{bmatrix}
T_{A_1B_1} & P_{A_1B_1} & C_{A_1B_1} \\
T_{A_2B_1} & P_{A_2B_1} & C_{A_2B_1} \\
... & ... & ... \\
T_{A_mB_1} & P_{A_mB_1} & C_{A_mB_1}
\end{bmatrix} = \begin{bmatrix}
15 & 0.6 & 500 \\
12 & 0.5 & 300 \\
... & ... & ...
\end{bmatrix}
$$
Set \( t = \max \{ T_{A_iB_j} \} = 24 \) and \( c = \max \{ C_{A_iB_j} \} = 1000 \), the column vectors \( T \) and \( C \) of the matrix \( Q \) are normalized according to Equation (2). The normalized transportation matrix \( \bar{Q} \) is expressed as:

\[
\bar{Q} = \begin{bmatrix}
\frac{T_{A_1B_1}}{t} & \frac{C_{A_1B_1}}{c} & 0.63 & 0.6 & 0.5 \\
\frac{T_{A_1B_2}}{t} & \frac{C_{A_1B_2}}{c} & 0.5 & 0.5 & 0.3 \\
\ldots & \ldots & \ldots & \ldots & \ldots \\
\frac{T_{A_1B_j}}{t} & \frac{C_{A_1B_j}}{c} & 0.54 & 0.8 & 0.5
\end{bmatrix}.
\]

The benefit indicator is converted into the cost indicator according to Equation (3), and the standardized matrix \( \bar{Q}' \) is expressed as follows:

\[
\bar{Q}' = \begin{bmatrix}
\frac{T_{A_1B_k}}{t} & \frac{C_{A_1B_k}}{c} & 0.63 & 0.4 & 0.5 \\
\frac{T_{A_1B_2}}{t} & \frac{C_{A_1B_2}}{c} & 0.5 & 0.5 & 0.3 \\
\ldots & \ldots & \ldots & \ldots & \ldots \\
\frac{T_{A_1B_j}}{t} & \frac{C_{A_1B_j}}{c} & 0.54 & 0.2 & 0.5
\end{bmatrix}.
\]

Using the experts grading method and combining the opinions of the after-sales service department and the actual demand, the weight coefficients of three transportation costs, i.e. transportation time, safe arrival probability and transportation charge, are defined as \((0.6, 0.3 \text{ and } 0.1)\), then \( W \) is expressed as:

\[
W = (W_T, W_P, W_C) = (0.6, 0.3, 0.1)
\]

The cost coefficient matrix \( K \) is calculated according to Equation (5):

\[
K = W \bar{Q}'^T = (0.6, 0.3, 0.1)
\]

\[
(0.55_{12}, 0.48_{12}, 0.68_{14}, 0.34_{24}, 0.42_{35}, 0.91_{39}, 0.47_{45}, 0.54_{46}, 0.69_{47}, 0.41_{56}, 0.83_{59}, 0.43_{67}, 0.44_{68}).
\]

According to the cost coefficient matrix \( K \), the schematic diagram for transportation route of maintenance spare parts is simplified to the schematic diagram for cost coefficient, as shown in Figure 2 below:

**Figure 2.** Schematic Diagram for Cost Coefficient of Maintenance Spare Parts Transportation Route

An effective route exploration algorithm (such as A-star algorithm) is adopted to calculate the route with minimum cost coefficient between the warehouse and the maintenance site. Such a route is considered as the optimal transportation route for maintenance spare parts, as shown in Table 2 below.
**Table 2. Optimal Transportation Route and Minimum Cost Coefficient Sum**

| Warehouse | Maintenance Site | Optimal Route | Minimum Duration | Average Arrival Probability | Minimum Charge | Minimum Cost Coefficient Sum |
|-----------|------------------|---------------|------------------|-----------------------------|----------------|-------------------------------|
|           | 1                | 7             | 1–4–7            | 40                          | 0.65           | 1500                          | 1.37 |
|           |                  | 8             | 1–4–6–8          | 51                          | 0.8            | 1930                          | 1.63 |
|           |                  | 9             | 1–3–9            | 36                          | 0.4            | 1300                          | 1.39 |
|           | 2                | 7             | 2–4–7            | 28                          | 0.6            | 830                           | 1.03 |
|           |                  | 8             | 2–4–6–8          | 39                          | 0.77           | 1260                          | 1.29 |
|           |                  | 9             | 2–4–5–9          | 44                          | 0.57           | 1430                          | 1.64 |
|           | 3                | 7             | 3–5–6–7          | 32                          | 0.67           | 1500                          | 1.26 |
|           |                  | 8             | 3–5–6–8          | 34                          | 0.7            | 1400                          | 1.24 |
|           |                  | 9             | 3–5–9            | 34                          | 0.55           | 1250                          | 1.25 |

According to the optimal transportation route between the warehouse and the maintenance site calculated above and the minimum cost coefficient on this route, as well as the known spare parts storage quantity and demand of each warehouse and maintenance site, the table for cost coefficient is formulated to define the minimum cost coefficient and the spare parts supply and demand relationship of each warehouse and maintenance site, as shown in Table 3 below:

**Table 3. Supply and Demand of Maintenance Spare Parts at Minimum Cost**

| Warehouse | Maintenance Site | 7 | 8 | 9 | Storage Quantity (pcs.) |
|-----------|------------------|---|---|---|--------------------------|
|           |                  | 1.37 | 1.63 | 1.39 | 1100                     |
| 1         |                  | 1.03 | 1.29 | 1.64 | 1200                     |
| 2         |                  | 1.26 | 1.24 | 1.25 | 1000                     |
| 3         | Demand (pcs.)    | 1300 | 700 | 1000 |                          |

The initial solution for the maintenance spare parts transportation scheme is calculated according to the minimum element method of the table-manipulation method on linear programming, as shown in Table 4 below:

**Table 4. Initial Solution for Maintenance Spare Parts Allocation and Transportation Scheme**

| Warehouse | Maintenance Site | 7 | 8 | 9 | Storage Quantity (pcs.) |
|-----------|------------------|---|---|---|--------------------------|
|           |                  | 100 | 700 |  | 1100                     |
| 1         |                  | 1200 | 700 |  | 1200                     |
| 2         |                  |       | 300 |  | 1000                     |
| 3         | Demand (pcs.)    | 1300 | 700 | 1000 |                          |
The potential method is used to test the calculated initial solution for the maintenance spare parts allocation and transportation scheme, and all test numbers are greater than zero, so the initial solution is considered as the optimal transportation scheme, as shown in Table 5 below.

**Table 5. Optimal Allocation and Transportation Scheme for Maintenance Spare Parts**

| Warehouse | Maintenance Site | 7   | 8   | 9   | Storage Quantity (pcs.) |
|-----------|-----------------|-----|-----|-----|-------------------------|
| 1         | 1               | 100 |     | 700 | 1100                    |
| 2         | 2               | 1200| 700 |     | 1200                    |
| 3         | 3               |     | 300 | 1000|                          |

| Demand (pcs.) | 1300 | 700 | 1000 |

To sum up, it can be seen that the optimal allocation scheme adopted by this household appliance manufacturer is to allocate 100 pieces from Warehouse 1 and 1200 pieces from Warehouse 2 to Maintenance Site 7, 700 pieces from Warehouse 2 to Maintenance Site 8, 700 pieces from Warehouse 1 and 300 pieces from Warehouse 3 to Maintenance Site 9. Then, the minimum cost sum of the optimal transportation scheme is calculated as: $100 \times 1.37 + 700 \times 1.39 + 1200 \times 1.03 + 700 \times 1.24 + 300 \times 1.25 = 3589$.

5. Brief Summary

Efficient after-sales service level has become one of the effective means to enhance the core competitiveness of an enterprise. How to improve the efficiency of spare parts allocation and save the maintenance servicing cost has become one of the bottleneck problems to be solved by all kinds of product manufacturers. On the basis of summarizing the domestic and foreign research results, this paper defines the main transportation cost of maintenance spare parts allocation, introduces the cost coefficient method, establishes a more simple and easy-to-use decision-making model for maintenance spare part allocation, and obtains the maintenance spare parts allocation scheme with minimum cost by combining A-star algorithm, table-manipulation method on linear programming and other methods, which provides a method support for improving the efficiency, scientificity and rationality of maintenance spare parts allocation of an enterprise.

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