Study on Evaluation Model of Equipment Transportation Efficiency Based on Analytic Hierarchy Process

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

¹China National Institute of Standardization, Beijing 100191, China
²China Ship Develop and Design Center, Wuhan 430064, China
³China standard promoting quality science and technology (beijing) co., ltd, Beijing 100191, China

* Corresponding author’s e-mail address: Peifei@cnis.ac.cn

Abstract. On the basis of factors influencing the evaluation of equipment transportation efficiency, such as safety, timeliness, universality and economy of system analysis, and in combination with the basic theory of Analytic Hierarchy Process (AHP), this paper sorted out the main steps for evaluation of equipment transportation efficiency, established the hierarchical chart for evaluation index of equipment transportation efficiency, proposed a comprehensive evaluation model of equipment transportation efficiency based on AHP, and verified the feasibility of this model through the specific cases. The comprehensive evaluation model of equipment transportation efficiency based on AHP proposed by this paper provides a method for the decision makers to select the optimal design scheme for equipment transportability, and lays a foundation for related studies of equipment transportability.

1. Introduction

Transportation efficiency is one of important indexes to evaluate the equipment readiness performance, and is also one of main factors affecting the outcome of a war [1]. The equipment transportation efficiency is closely related to the reliability of transportability design scheme, expenses and expenditures, universality of transportation equipment, transportation time, etc. Therefore, the transportation efficiency evaluation of equipment transportability design scheme pertains to a multi-attribute and complicated decision-making problem analysis. And AHP can analyze the multiple influencing factors of the complicated decision-making problem and their interaction well, decompose the decision-making problems level upon level through a combination of qualitative and quantitative methods, and determine the optimal scheme. Therefore, it is widely used in all fields. Dongzhi Wang, et al. (2019) [2], Yu Lu, et al. (2019) [3], Yang Wang, et al. (2019) [4], Chen Li, et al. (2019) [5], and Yanfeng Zhang (2019) [6] respectively applied the AHP to the evaluation of groundwater quality, weight determination of road in the driving condition, comprehensive monitoring of transmission section, power grid dispatching evaluation, multi-attribute threat evaluation of equipment, etc. Guoquan Yan, et al (2017) [7] applied the AHP to the risk analysis and assessment of transportation and construction supervision, and established a comprehensive evaluation model to determine the project risk. Jiayong Zhu, et al. (2019) [8] used the AHP to analyze the influence relationship among overall control, resource input, coordination workload, procedure complexity, cost controllability and quality safety risk level of port construction project, and established an analytic hierarchy model, thereby providing a reasonable and reliable basis for the project undertaker to make decision.
On the basis of the above research results and in combination with the factors influencing the evaluation of equipment transportation efficiency, this paper established the evaluation model of equipment transportation efficiency based on AHP, thereby providing a scientific method for selection of optimal equipment transportability design scheme.

2. Factors Influencing Equipment Transportation Efficiency

There are many factors influencing the equipment transportability efficiency, mainly including the safety, economy, universality and timeliness [9, 10].

2.1. Safety

Safety of equipment transportation process has a direct influence on smooth assembly or prompt use of equipment to be transported after its arrival at the destination, and is one of important factors influencing the equipment transportation efficiency. Safety factor is usually expressed by the reliability of equipment transportability design scheme to accomplish the equipment transportation task.

2.2. Economy

Equipment transportation involves packaging, loading and unloading, storage, transportation and other activities, each link of which will generate the expenses on personnel, maintenance, energy consumption and leasing. How to achieve the maximum benefit at the lowest cost is also a key consideration in the equipment transportability design scheme.

2.3. Universality

The more the kinds, quantities and volumes of special resources consumed in equipment transportation are, the more the time and expenditures consumed in the transportation process are. Therefore, the reduction of ratio of special transportation resources in the total transportation resources during the equipment transportation is also one of main methods to improve the equipment transportation efficiency.

2.4. Timeliness

Reasonable and efficient utilization of existing personnel and equipment resources to deliver the equipment to be transported to the destination on time and in good condition is a precondition to ensure the equipment readiness. Under the equal conditions, the higher the timeliness is, the better the equipment transportability design scheme is.

3. Evaluation Model of Equipment Transportation Efficiency Based on AHP

3.1. Basic Theory of AHP

AHP refers to establishing an index hierarchy and judgment matrix by applying the network system theory and multi-objective comprehensive evaluation method and analyzing the influencing factors, calculating the index weight with the mathematical method, and conducting the consistency check to obtain the weight of index in each hierarchy.

3.1.1. Establishment of progressive hierarchy. AHP divides the index into different hierarchies, generally including the objective level, criterion level and scheme level. The objective level mainly refers to the predetermined objective of the problem, the criterion level generally refers to the relevant criteria affecting the objective achievement and can also be further subdivided into sub-criterion level as required, and the scheme level refers to the schemes related to the objective achievement, specifically as shown in Figure 1.
3.1.2. Construction of judgment matrix. The judgment matrix is constructed according to the hierarchical structure. Each element having downward subordination is taken as the first element of judgment matrix, and elements attached to it are successively arranged in the first row and first column of the climate. Associated elements are compared pairwise, and assigned 1 to 9 according to the importance. Refer to Table 1 for the scale value of importance.

Table 1. Scale Value of Importance

| Scale value of importance | Degree to which one factor is more important than the other one by comparing them |
|---------------------------|---------------------------------------------------------------------------------|
| 1                         | Equally important                                                              |
| 3                         | Slightly important                                                             |
| 5                         | Obviously important                                                            |
| 7                         | Strongly important                                                             |
| 9                         | Absolutely important                                                           |
| 2,4,6,8                   | Median of the above adjacent judgment                                           |
| Inverse                   | If $A_i$ is compared with $A_j$ to obtain $A_{ij}$, $A_j$ and $A_i$ are compared to obtain $A_{ji} = \frac{1}{A_{ij}}$ |

Thus, the judgment matrix $A = (A_{ij})_{n \times n}$ can be obtained, as shown in Table 2:

Table 2. Elements of Judgment Matrix A

| $A_{ij}$ | $A_1$ | $A_2$ | ...... | $A_n$ |
|----------|-------|-------|--------|-------|
| $A_1$    | 1     | $A_{12}$ | ...... | $A_{1n}$ |
| $A_2$    | $A_{21}$ | 1     | ...... | $A_{2n}$ |
| ......    | ...... | ...... | ...... | ...... |
| $A_n$    | $A_{n1}$ | $A_{n2}$ | ...... | 1     |
\[ A_{ij} = \frac{A_{ij}}{\sum_{k=1}^{n} A_{kj}} \]  \hspace{1cm} (1)

Where, \( i, j = 1, 2, \ldots, n \).

- Adding the rows of normalized judgment matrix

\[ W_i = \frac{1}{\sum_{j=1}^{n} A_{ij}} \]  \hspace{1cm} (2)

Where, \( i, j = 1, 2, \ldots, n \).

- Normalizing the vector \( W \) to obtain the eigenvector

\[ W_i = \frac{W_i}{\sum_{j=1}^{n} W_j} \]  \hspace{1cm} (3)

Where, \( i, j = 1, 2, \ldots, n \).

- Calculating the maximum eigenvalue

\[ \lambda_{\text{max}} = \sum_{i=1}^{n} \left( AW \right)_i = \frac{\sum_{i=1}^{n} (AW)_i}{n} \]  \hspace{1cm} (4)

Where, \( i = 1, 2, \ldots, n \).

3.1.4. Consistency check. During the pairwise comparison for importance of indexes, there may be some errors, and thus, the consistency cannot be satisfied. In order to ensure the rationality of determining the weight with the AHP, it is necessary to check the consistency of the judgment matrix.

- Calculating the consistency index C.I.

\[ C.I. = \frac{\lambda_{\text{max}} - n}{n - 1} \]  \hspace{1cm} (5)

- Determining the corresponding average random consistency index R.I. through table look-up, as shown in Table 3.

**Table 3. R.I. Repeatedly Calculated for 1,000 Times**

| n   | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  | 11  | 12  |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| R.I.| 0.00| 0.00| 0.52| 0.89| 1.12| 1.26| 1.36| 1.41| 1.46| 1.49| 1.52| 1.54|

- Calculating the consistency ratio C.R.

\[ C.R. = \frac{C.I.}{R.I.} \]  \hspace{1cm} (6)

Generally, when C.R.<0.1, the consistency of the judgment matrix is considered acceptable. Otherwise, the judgment matrix does not meet the consistency requirement and needs to be revised again.

3.2. Comprehensive Evaluation Model of Transportation Efficiency

In this paper, the comprehensive weighted evaluation method is adopted to determine the transportation efficiency of equipment transportability design scheme on the basis of obtaining the weight vectors of indexes. Assuming that there are \( n \) alternative equipment transportability design schemes and \( m \) evaluation indexes, a decision-making matrix \( B \) is established by combining the alternative transportability design scheme with the transportation efficiency evaluation indexes, and can be expressed as:

\[ B = (b_{ij})_{m \times n} \]  \hspace{1cm} (7)

Where, \( i = 1, 2, \ldots, m; j = 1, 2, \ldots, n; b_{ij} \) refers to the attribute value when the \( j \)-th equipment transportation scheme corresponds to the \( i \)-th evaluation index.

The transportation efficiency of alternative scheme can be calculated in accordance with the weight vectors of the indexes and the decision-making matrix \( B \), and expressed by \( Z \):

\[ Z_j = \sum_{i=1}^{n} W_i b_{ij} \]  \hspace{1cm} (8)

Where, \( i = 1, 2, \ldots, m; j = 1, 2, \ldots, n \).
The higher the multi-factor comprehensive evaluation value of equipment transportation efficiency is, the better the comprehensive consideration result of this transportation scheme is, and is expressed by $Z^*_j$ which is specifically calculated as follows:

$$Z^*_j = \max\{Z_j | j = 1, 2, ..., n\}$$  \hspace{1cm} (9)

So it can be obtained that, the equipment transportation scheme $j$ is the optimal transportation scheme.

4. Case Analysis

4.1. Basic Information

The hierarchical chart for evaluation index of transportation efficiency of newly developed equipment is established in combination with the analysis on influencing factors of equipment transportation efficiency [9, 10], as shown in Figure 2.

![Evaluation Index Hierarchy for Traffic Transportation Efficiency of Equipment](image)

**Figure 2. Evaluation Index Hierarchy for Traffic Transportation Efficiency of Equipment**

Ten experts are organized to grade the transportation efficiency indexes of all schemes according to the basic information table for alternative scheme of equipment (refer to Table 4), and to discretize them according to the ceiling principle, to obtain the decision table of transportation efficiency evaluation (refer to Table 5).

**Table 4. Basic Information Table of Equipment Transportability Design Scheme**

| Scheme | Safety (%) | Economy (RMB 10,000) | Universality (%) | Timeliness (%) |
|--------|------------|----------------------|------------------|---------------|
| $A_1$  | 97         | 10                   | 70               | 80            |
| $A_2$  | 95         | 15                   | 80               | 80            |
| $A_3$  | 96         | 11                   | 60               | 90            |
| $A_4$  | 95         | 12                   | 70               | 80            |
| $A_5$  | 94         | 13                   | 80               | 70            |
| $A_6$  | 97         | 12                   | 80               | 80            |
Table 5. Decision Table after Discretization

| Scheme | $C_1$ | $C_2$ | $C_3$ | $C_4$ | $C_5$ | $C_6$ | $C_7$ | $C_8$ | $C_9$ | $C_{10}$ | $C_{11}$ | $C_{12}$ |
|--------|-------|-------|-------|-------|-------|-------|-------|-------|-------|---------|---------|---------|
| $A_1$  | 5     | 5     | 4     | 3     | 3     | 3     | 2     | 4     | 4     | 3       | 3       | 4       |
| $A_2$  | 5     | 4     | 4     | 1     | 2     | 4     | 3     | 4     | 5     | 3       | 3       | 4       |
| $A_3$  | 4     | 3     | 5     | 4     | 4     | 5     | 5     | 4     | 5     | 3       | 4       | 4       |
| $A_4$  | 3     | 4     | 4     | 3     | 4     | 3     | 4     | 3     | 4     | 3       | 4       | 4       |
| $A_5$  | 5     | 4     | 3     | 1     | 2     | 5     | 4     | 4     | 5     | 4       | 4       | 3       |
| $A_6$  | 1     | 5     | 5     | 5     | 2     | 2     | 2     | 2     | 3     | 3       | 3       | 4       |
| $A_7$  | 2     | 3     | 5     | 3     | 5     | 1     | 4     | 3     | 3     | 3       | 4       | 4       |
| $A_8$  | 3     | 4     | 4     | 3     | 5     | 5     | 3     | 4     | 5     | 4       | 5       | 5       |

4.2. Weight Calculation of Index

In this case, detailed calculation is conducted with the sum product by taking the index of the criterion level in the hierarchical chart for evaluation index of equipment transportation efficiency as an example, with the specific process as follows:

4.2.1. Establishing the judgment matrix and normalizing it. Determining and establishing the judgment matrix according to the ratio scales of 1-9 in Table 1, comparing the matrix $A = (a_{ij})_{n \times n}$ according to the importance, and normalizing each column of the judgment matrix to obtain:

$$A = \begin{bmatrix}
1 & 1/2 & 5 & 4 \\
2 & 1 & 6 & 5 \\
1/5 & 1/6 & 1 & 1/3 \\
1/4 & 1/5 & 3 & 1
\end{bmatrix}$$

So:

$$\bar{A} = \begin{bmatrix}
0.2899 & 0.2679 & 0.3333 & 0.3871 \\
0.5797 & 0.5357 & 0.4000 & 0.4839 \\
0.0580 & 0.0893 & 0.0667 & 0.0323 \\
0.0725 & 0.1071 & 0.2000 & 0.0968
\end{bmatrix}$$

4.2.2. Adding the rows of normalized judgment matrix. Adding the normalized judgment matrix by rows to obtain the vector $\bar{W} = (\bar{w}_1, \bar{w}_2, \ldots, \bar{w}_n)^T$ as follows:

$$\bar{W} = \begin{bmatrix}
1.2781 \\
1.9993 \\
0.2462 \\
0.4764
\end{bmatrix}$$

4.2.3. Solving the eigenvector. Normalizing the vector $\bar{W} = (\bar{w}_1, \bar{w}_2, \ldots, \bar{w}_n)^T$ to obtain the solved eigenvector $W = (w_1, w_2, \ldots, w_n)^T$, namely, the weight vector of index in the criterion level, as follows:

$$W = \begin{bmatrix}
0.3195 \\
0.4998 \\
0.0615 \\
0.1191
\end{bmatrix}$$

So:

$$BW = \begin{bmatrix}
1.3536 \\
2.1036 \\
0.2485 \\
0.4836
\end{bmatrix}$$
4.2.4. **Solving the maximum eigenvalue.** Calculating the maximum eigenvalue $\lambda_{max}$ of the judgment matrix. The following equation is obtained by BW and $w_i$:

$$
\lambda_{max} = \sum_{i=1}^{n} \left( \frac{(BW)_i}{n w_i} \right) = \frac{1.3536}{4 \times 0.3195} + \frac{2.1036}{4 \times 0.4998} + \frac{0.2485}{4 \times 0.0615} + \frac{0.4836}{4 \times 0.1191} = 4.1355
$$

4.2.5. **Consistency check.** The consistency check index C.I. could be obtained according to the maximum eigenvalue of the judgment matrix:

$$
C.I. = \frac{\lambda_{max} - n}{n - 1} = \frac{4.1355 - 4}{4 - 1} = 0.0452
$$

Then, based on Table 3, the consistency index RI could be obtained, and the consistency ratio C.R. is calculated as follows:

$$
C.R. = \frac{C.I.}{R.I.} = \frac{0.0452}{0.89} = 0.0508 < 0.1
$$

Accordingly, it could be determined that, the judgment matrix has satisfied consistency, and thus, the relative weights of four indexes in the criterion level are determined. Similarly, repeating the above processes, the weights of all indexes in the sub-index level could be determined, and finally, the weight relationship among the indexes is determined, as shown in Table 6 below:

**Table 6. Subjective Weights of Indexes**

| Attribute | Weight | Attribute | Weight | Attribute | Weight | Attribute | Weight |
|-----------|--------|-----------|--------|-----------|--------|-----------|--------|
| $C_1$     | 0.1023 | $C_4$     | 0.1999 | $C_7$     | 0.0205 | $C_{10}$  | 0.0244 |
| $C_2$     | 0.1757 | $C_5$     | 0.1749 | $C_8$     | 0.0266 | $C_{11}$  | 0.0422 |
| $C_3$     | 0.0415 | $C_6$     | 0.1250 | $C_9$     | 0.0145 | $C_{12}$  | 0.0525 |

4.3. **Transportation Efficiency Evaluation**

The decision tables and weight vectors of discretized indexes could be respectively obtained according to Table 5 and Table 6, and in combination with Formula (8), the equipment transportation efficiency of each transportability design scheme is comprehensively evaluated, and the evaluation result is shown in Table 7.

**Table 7. Comprehensive Evaluation Result of Equipment Transportability Design Scheme**

| Alternative scheme | Comprehensive evaluation value of transportation efficiency | Ranking of evaluation result |
|--------------------|----------------------------------------------------------|-----------------------------|
| $A_1$              | 3.7956                                                   | 3                           |
| $A_2$              | 3.0802                                                   | 8                           |
| $A_3$              | 4.1045                                                   | 1                           |
| $A_4$              | 3.4895                                                   | 4                           |
| $A_5$              | 3.1983                                                   | 6                           |
| $A_6$              | 3.7684                                                   | 4                           |
| $A_7$              | 3.1535                                                   | 7                           |
| $A_8$              | 4.0541                                                   | 2                           |
The comprehensive evaluation result for transportation efficiency of equipment transportability design scheme obtained from the above table shows that, the Scheme A_3 is the optimal design scheme, and the Scheme A_8 is the suboptimal design scheme. The comprehensive evaluation results of transportation efficiency for these two schemes are significantly better than those of other six schemes, and there is little difference in the evaluation results of the two schemes. Therefore, the decision makers are suggested to select one of the two schemes A_3 and A_8 as the transportability design scheme of this equipment.

5. Summary
As the recognition of importance to the equipment transportation efficiency evaluation is gradually increased, the research in this field in China is also gradually deepened. The comprehensive evaluation model of equipment transportation efficiency based on AHP proposed by this paper is imperfect, but combines the qualitative and quantitative methods to a certain extent. This concept is introduced into the field of equipment transportation efficiency evaluation, thereby providing a more scientific method for the decision makers to select the optimal equipment transportability design scheme, and having certain reference significance for follow-up study on equipment transportability analysis.

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References
[1] Qian Wu. Study on Transportability Analysis Method of Unmanned Aerial Vehicle System [D]. Beijing: Beihang University, 2014.
[2] Dongzhi Wang, Jianhui Liang. Evaluation on Groundwater Quality Based on Analytic Hierarchy Process - Taking Aksu as an Example [J]. Journal of Anhui Agricultural Sciences, 2019, 47 (8): 80-85.
[3] Yu Lu. Weight Determination of Road in Driving Condition Based on Analytic Hierarchy Process [J], Test, 2019 (2): 114-117.
[4] Yang Wang, Biao Xu, Chaofan Zhou, et al. Comprehensive Monitoring Method of Transmission Section Based on Analytic Hierarchy Process [J]. China Power, 2019, 52 (4): 89-95.
[5] Cheng Li, Zili Yin, Xiaohui Wang, et al. Dispatching Evaluation of Power Distribution Network Based on Analytic Hierarchy Process and Entropy Weight Method [J]. Proceedings of the CSU-EPSA, 2019: 1-8.
[6] Yanfeng Zhang, Jianshu Liu, Shifeng Zhang. Multi-attribute Threat Evaluation of Objective Based on Analytic Hierarchy Process and Entropy Method [J]. Journal of Projectiles, Rockets, Missiles and Guidance, 2019, 2:1-6.
[7] Guoquan Yan, Hongwei Chen. Study and Application of Analytic Hierarchy Process in Risk Analysis and Assessment of Construction Supervision of Waterway Engineering [J]. Management and Administration, 2017, 24 (12): 230-235.
[8] Jiayong Zhu, Hang Su. Discussion of Port Construction Mode Based on Analytic Hierarchy Process [J]. Port & Waterway Engineering, 2019, 554 (4): 89-94.
[9] Qian Wu, Ma Lin, Chaowei Wang. Study on Evaluation Index System of Equipment System Transportability [C], WCEAM2013, 2015: 1539-1547.
[10] Lei Zhang, Yumpeng Chen, Minglu Guan. Study on Evaluation Model of Military Air Transportation Efficiency in Wartime [J]. Fire Control & Command Control, 2013, 38 (3): 69-75.