Auxiliary Decision of Signal System Renovation Scheme for Urban Rail Transits

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Abstract. In a renovation of urban rail transit (URT) signal systems, the renovation scheme runs through the whole process of the renovation, and it is necessary to solve the problem of the comparison and decision-making of the plan. Through sorting out the relevant results of renovations, the renovation methods are classified into three categories: repair as old, upgrade and replacement, and upgrade and compatibility. For the renovation scheme, the renovation scheme selection index system including 4 dimensions and 14 sub-dimensions is constructed. Furthermore, the renovation scheme selection auxiliary decision algorithm based on fuzzy multi-attribute decision is proposed. The results of the case study fit well with an existing project, which verifies the effectiveness of the method and reflects the multi-attribute characteristics of the signal system renovation scheme. The proposed method can provide quantitative decision support for signal system renovations.

Keywords: urban rail transit, signal system, renovation, scheme selection, fuzzy multi-attribute decision

1 INTRODUCTION

The document, Management Method for the Operation and Maintenance of Urban Rail Transit Facilities and Equipment, released by Ministry of Transport of the People's Republic of China in 2019 stipulates that the overall service life of the signal system is generally less than 20 years. Renovation is an important part of the whole life cycle of the signal system, and it is a necessary way to guarantee and improve the quality of operation. According to statistics, more than 10 lines in China have been in operation for more than 20 years, and more than 31 lines have been in operation for more than 15 years.

The existing renovation projects show that the selection of renovation schemes is a necessary procedure to promote. Technicians and managers are very concerned about this at this stage and have discussed the selection of renovation schemes [1-4], but most of them are based on qualitative analysis. However, the qualitative analysis has strong subjectivity and depends more on the will of the decision maker, especially when the decision maker is relatively single. Quantitative decision is more objective. Based on this, combined with previous studies, the auxiliary decision method of URT signal

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system renovation scheme is discussed in this paper to provide quantitative decision method for related practice.

2 AUXILIARY DECISION INDEX SYSTEM

Signal system renovation requirements have differentiated characteristics, and different projects have different requirements for the scope of renovation, renovation period, new technology application, and transportation capacity improvement, which requires consideration of the detailed and customized characteristics of the renovation plan. Such projects are faced with such difficulties as project approval, passenger flow pressure, operation stability, program formulation and optimization, organization and management, etc. Therefore, the analysis, improvement and decision-making of renovation scheme are important. When there are more access or alternative renovation schemes, it is also necessary to carry out the comparison of schemes. At this time, the construction of a corresponding auxiliary decision index system is helpful for decision-making.

In previous studies, Zhang [2] compared the schemes from the perspectives of system design, interface with other specialties, difficulty of project implementation, requirements of site conditions, system commissioning, on-board equipment commissioning, impact on operation, operational safety risks, project procurement bidding, project cost, technical support and spare parts supply during operation, and technical application maturity. Wang [3] believed that the factors affecting the renovation included economic and social benefits, technical and construction difficulties, operation and maintenance, and safety. At the same time, Zhang [1] discussed the choice of signal system renovation scheme from the perspectives of technology, economy and implementeability.

It can be seen that when carrying out the comparison of renovation schemes, it should be considered comprehensively. Based on previous studies, an index system is proposed, as shown in Table 1, including corresponding connotations and attributes. Among them, the economy reflects the economic characteristics of a renovation scheme, the technology reflects the technical characteristics, the implemensibility represents the implementation characteristics, and the applicability reflects the expected operational characteristics of the renovation signal system. In this paper, the index that the higher the quantization value, the more it meets the demand, is classified as the income type index. Otherwise, it is a cost type index.

Table 1. Selection index system of signal system renovation scheme.

Index and its connotation			Index attribute	
Dimension	Sub-dimension	Connotation	Cost type	Income type
Economy	Renovation cost	Expected total retrofit cost of the system	√	--
	Operating cost	Expected energy consumption of the system	√	--

	Maintenance cost	Expected maintenance costs to keep the system functional	√	--
Technology	Technology advancement	Degree of advancement, fit with the development trend	--	√
	Technology maturity	Degree of functional perfection or practical application	--	√
	RAMS features	Reliability, availability, maintainability, and security-related metrics	--	√
Implementability	Implementation difficulty	Implementation difficulty of renovation process (relative to implementer)	√	--
	Management difficulty	Difficulty of managing and coordinating the renovation process (relative to the manager)	√	--
	Boundary matching	Fitness with budget, existing facilities, schedule, etc.	--	√
	Operational impact	Impact degree of the renovation on daily operations	√	
Applicability	Operation matching	Expected matching degree between equipment operation capability and passenger flow demand	--	√
	Spare parts	Adequacy of spare parts	--	√
	Degree of autonomy	Autonomy of software, hardware and services	--	√
	Expected service life	Expected overall service life of the system	--	√

3 AUXILIARY DECISION ALGORITHM

When faced with multiple feasible signal system renovation plans, it is necessary to carry out comparison and decision. Based on the constructed index system, this paper designs a quantitative selection algorithm for signal system renovation scheme based on fuzzy multi-attribute decision [5][6], as follows:

Step 1: Quantify the observed indexes of each candidate scheme and obtain the index matrix. For a qualitative index, the quantitative transformation should be carried out by combining the attributes of the index and the triangular fuzzy number ratio method, as shown in Figure 1. At the same time, for the quantitative index, it only needs to be written out in the form of triangular fuzzy number. For example, if an index is 100, its triangular fuzzy number form is (100, 100, 100).

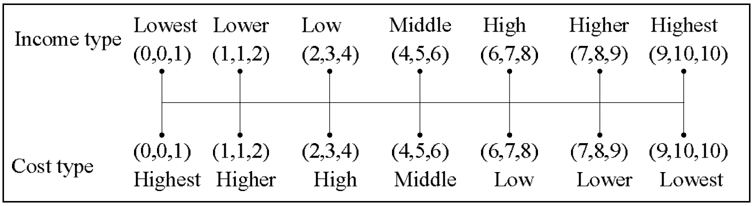

Fig. 1. Triangular fuzzy number ratio method.

Assuming that there are *m* alternatives and *n* observation indexes, the index matrix can be expressed as:

$$\boldsymbol{V} = \begin{bmatrix} v_{11} & v_{12} & \cdots & v_{1n} \\ v_{21} & v_{22} & \cdots & v_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ v_{m1} & v_{m2} & \cdots & v_{mn} \end{bmatrix} \quad (1)$$

where, the fuzzy form of the data v_{ij} of the *j*th observation index for the *i*th alternative renovation is (a_{ij}, b_{ij}, c_{ij}).

Step 2: Normalize the index matrix according to the attributes of each index. Different types of indexes have different normalization methods. Here, $(z \wedge 1)$ represents the comparation of value z and 1, taking the corresponding minimum value, i.e., $(z \wedge 1) = \min(z,1)$. If v_{ij} is a cost type index, its normalization method is:

$$v_{ij}^{'} = \left(\frac{\min(a_{:,j})}{c_{i,j}}, \frac{\min(b_{:,j})}{b_{i,j}}, \frac{\min(c_{:,j})}{a_{i,j}} \wedge 1 \right) \quad (2)$$

where, $\min(a_{:,j})$ takes $\min(a_{1,j}, a_{2,j}, \cdots, a_{m,j})$. It's similar for $\min(b_{:,j})$ and $\min(c_{:,j})$.

If v_{ij} is an income type index, its normalization method is:

$$v_{ij}^{'} = \left(\frac{a_{i,j}}{\max(c_{:,j})}, \frac{b_{i,j}}{\max(b_{:,j})}, \frac{c_{i,j}}{\max(a_{:,j})} \wedge 1 \right) \quad (3)$$

where, $\max(a_{:,j})$ takes $\max(a_{1,j}, a_{2,j}, \cdots, a_{m,j})$. It's similar for $\max(b_{:,j})$ and $\max(c_{:,j})$.

After observation data is normalized by the above way, the normalized index matrix $\boldsymbol{V}' = \left[v'_{ij}\right]_{m\times n}$ can be obtained. Here, the triangular fuzzy number form of v'_{ij} is $(a'_{ij}, b'_{ij}, c'_{ij})$.

Step *3: Calculate the weight of each index and reconstruct the weight vector with triangular fuzzy number form*. The weight can be determined by subjective weighting or objective calculation. For an initial weight vector $\boldsymbol{w} = (w_1, w_2, \cdots, w_j, \cdots, w_n)$ (w_j is the weight of the *j*th index), the triangular fuzzy number form is:

$$\boldsymbol{w}' = (w_1, w_1, w_1, w_2, w_2, w_2, \cdots, w_n, w_n, w_n) \tag{4}$$

Step *4: Weight the normalized index matrix to construct the decision matrix*. A simple weighting method is adopted in this paper. For any index data v'_{ij}, the weighting calculation method is:

$$v''_{ij} = (w_j \times a'_{ij}, w_j \times b'_{ij}, w_j \times c'_{ij}) \tag{5}$$

Step *5: Determine the positive ideal and negative ideal*. The positive ideal M^+ consists of the optimal values of each index in all schemes. The negative ideal M^- consists of the corresponding worst values. Specifically:

$$\begin{cases} \mathrm{M}^+ = (m_1^+, m_2^+, \cdots, m_n^+) \\ \mathrm{M}^- = (m_1^-, m_2^-, \cdots, m_n^-) \end{cases} \tag{6}$$

where, m_j^+ takes $\max(v''_{1j}, v''_{2j}, \cdots, v''_{mj})$ (if index j is an income-type index) or $\min(v''_{1j}, v''_{2j}, \cdots, v''_{mj})$ (if index j is a cost-type index), m_j^- takes $\max(v''_{1j}, v''_{2j}, \cdots, v''_{mj})$ (if index j is a cost-type index) or $\min(v''_{1j}, v''_{2j}, \cdots, v''_{mj})$ (if index j is an income-type index).

Step *6: Determine the distance of each candidate from the positive ideal and the negative ideal*. For candidate *i*, determine its distance d_i^+ from the positive ideal and its distance d_i^- from the negative ideal in terms of the Euclidean distance:

$$\begin{cases} d_i^+ = \sqrt{\sum_{j=1}^{n} (v''_{ij} - m_j^+)^2} \\ d_i^- = \sqrt{\sum_{j=1}^{n} (v''_{ij} - m_j^-)^2} \end{cases} \tag{7}$$

Step 7: Calculate the relative benefit value of each candidate scheme and determine the reference order of the advantages and disadvantages of the candidate scheme. We can calculate the relative benefit value u_i of the ith candidate by:

$$u_i = \frac{d_i^-}{d_i^+ + d_i^-} \tag{8}$$

Obviously, the closer the decision vector of the candidate scheme is to the positive ideal, the larger the value of u_i is, the closer to 1. And the smaller it is, the closer to 0. By ordering the relative benefit value of each candidate scheme from large to small, the reference order of each candidate scheme can be obtained.

4 NUMERICAL ANALYSES

In order to analyze the effectiveness of the above selection method, combined with the index system, the Figure 1, the data in Literature [1] and the opinions of five experts, the example data and the total hierarchical ranking weights of each index are shown in Table 2. In Table 2, Scheme 1 represents a scheme that uses the existing system, Scheme 2 represents a scheme that upgrades and replaces the existing system, and Scheme 3 represents a scheme that upgrades the existing system and is compatible with the existing system.

Table 2. Numerical data.

Index (Weight)	Scheme 1	Scheme 2	Scheme 3
Expected renovation cost (0.067)	Low	Middle	Middle
Expected operating cost (0.042)	High	Middle	High
Expected maintenance cost (0.058)	High	Middle	Middle
Technological advancement (0.067)	Low	High	Higher
Technology maturity (0.100)	High	High	High
RAMS Characteristics (0.167)	Middle	High	Higher
Implementation difficulty (0.050)	Low	High	Low
Management difficulty (0.050)	Low	High	Low
Boundary matching (0.063)	Middle	Middle	Middle
Operational impact (0.088)	Low	High	Lower
Operation matching (0.075)	Low	High	Higher
Spare parts (0.050)	High	High	High
Degree of autonomy (0.075)	High	High	High
Expected service life (0.050)	High	High	High

With the help of MATLAB software, the above auxiliary decision algorithm was programmed, and the data to be evaluated was brought in. And the results obtained are shown in Table 3. And the results in Table 3 show the characteristics of multi-attribute decision.

Specifically, in Table 3, for economy, Scheme 2 is the best, Scheme 3 is second, Scheme 1 is the worst; for technology, Scheme 3 is the best, Scheme 2 is second, Scheme 1 is the worst; for implementability, Scheme 3 is the best, Scheme 1 is the second, Scheme 2 is the worst; for applicability, Scheme 1 is the best, Scheme 2 is second, and Scheme 1 is the worst. At the same time, considering all kinds of indexes, Scheme 3 is the most appropriate, and this result is consistent with the conclusion in Literature [1]. As for Scheme 2, its economy, technology and applicability are better than Scheme 1, and it is also better than Scheme 3 in economy. The overall reason why it is inferior to Scheme 3 is that it is slightly less technical, implementable and applicable. For Scheme 1, its technology and applicability are poor, the consistency of the corresponding passenger flow demand and technical demand for renovation demand is low, but the implementation is better than Scheme 2, which is related to its corresponding to the existing standard. In addition, based on the results of Table 3, Scheme 2 could be improved in terms of implementability and adaptability to enhance competitiveness.

Table 3. Relative benefit values between dimensional indexes and overall situation.

Index (Weight)	Scheme 1	Scheme 2	Scheme 3
Economy (0.167)	0.417	0.583	0.467
Technology (0.334)	0	0.729	1
Implementability (0.249)	0.890	0	1
Applicability (0.250)	0	0.826	1
Overall situation	0.383	0.526	0.845

5 CONCLUSION

The renovation of URT signal system needs to solve the problems of project declaration, scheme preparation, scheme selection and optimization, scheme implement, etc. Quantitative decision-making is very important for the whole process of signal system renovation. Aiming at the selection of renovation schemes, this paper studies the corresponding index system and selection methods, forming a selection method for signal system renovation schemes, and providing methodological support and practical basis for quantitative decision-making of URT signal system renovation. The further study can focus on the comparison of different selection methods and the selection methods for other similar systems.

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