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Multilevel Fuzzy Decision Support Model for China's Urban Rail Transit Planning Schemes

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Abstract**—**This paper aims at developing a multilevel fuzzy decision support model for urban rail transit planning schemes in China under the background that China is presently experiencing an unprecedented construction of urban rail transit. In this study, an appropriate model using multilevel fuzzy comprehensive evaluation method is developed. In the decision process, the followings are considered as the influential objectives: traveler attraction, environment protection, project feasibility and operation. In addition, consistent matrix analysis method is used to determine the weights between objectives and the weights between the objectives' sub-indictors, which reduces the work caused by repeated establishment of the decision matrix on the basis of ensuring the consistency of decision matrix. The application results show that multilevel fuzzy decision model can perfectly deal with the multivariable and multilevel decision process, which is particularly useful in the resolution of multilevel decision-making problem of urban rail transit planning schemes.

Keywords**—**Urban rail transit, planning schemes, multilevel fuzzy decision support model, consistent matrix analysis

I. Introduction

OVER the past few decades, rapid urban expansion due to urbanization and economic growth has drastically increased the size of both mega-city and medium-city in China. Meanwhile, traffic congestion caused by sharp addition of urban travel demand and drawback of transportation infrastructure has become more and more serious in China. These problems have been compounded by growing urban auto traffic, which has increased competition for limited road space and time. Under this background, local authorities have launched rail transit development projects, which include construction of new rail transit lines and extension of existing rail transit lines. By the end of 2010, 12 cities in China, including Beijing, Shanghai, Hong Kong, etc., had constructed rail transit lines total up to 1,395 km with 48 lines under operation [1]. There are another 28 cities, including Suzhou, Wuhan, Xi'an, etc., have been approved by China's State Council, are planning or constructing rail transit projects. By 2015, China plans to construct 96 rail transit lines. The total mileage will be 2,550 km and the total investment planned to exceed one trillion. Undoubtedly, China is experiencing an unprecedented construction of urban rail transit as well as becomes one of the largest construction markets of urban rail transit worldwide.

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With such large scale of rail transit construction in China, how to choose the optimal rail transit alternative planning schemes for cities is a critical problem at present. Researchers have done hard work dealing with the problem of selecting optimal urban rail transit planning schemes in China. They made comparison on the alternatives and decided optimal planning schemes on the basis of different evaluation methods, such as AHP-TOPSIS selection method [2], fuzzy expandable engineering method [3], grey relation method [4], etc. These methods have unequal advantages as well as different disadvantages. One of the common disadvantages is that the researchers did not consider the development objectives of cities in the process of rail transit's planning and construction.

This study emphasizes on developing a multilevel fuzzy decision support model for China's local authorities to support their decision-making skills in urban rail transit planning and development with integrating Chinese context. Traveler attraction, environmental protection, project feasibility and operation are identified in the decision-making model of urban rail transit projects choice. Multilevel fuzzy comprehensive evaluation is used to validly reflect the hierarchical characteristic of screening alternative urban rail transit planning schemes. In the proposed model, consistent matrix analysis method is used for determining relative importance of objectives and their included factors, which can avoid the additional workload of consistency check process in traditional AHP method. The proposed model is accurately described in the decision process of Suzhou's urban rail transit planning schemes to select the superior urban rail transit planning scheme.

II. Scheme Background And Considered Factors

Suzhou is a major city located in the southeast of Jiangsu Province in Eastern China, which has over 2,500 years of rich history with an urban population of over 4 million expanding to over 10 million in the administrative area by the end of 2010. Suzhou presently plans to build an urban rail transit network with three alternative planning schemes. Before making a decision, the decision-makers together with experts in the field of urban rail transit select four objectives composed by ten sub-indicators to reflect the characteristics of the alternative planning schemes. These four objectives and their ten sub-indicators are showed in Fig. 1.

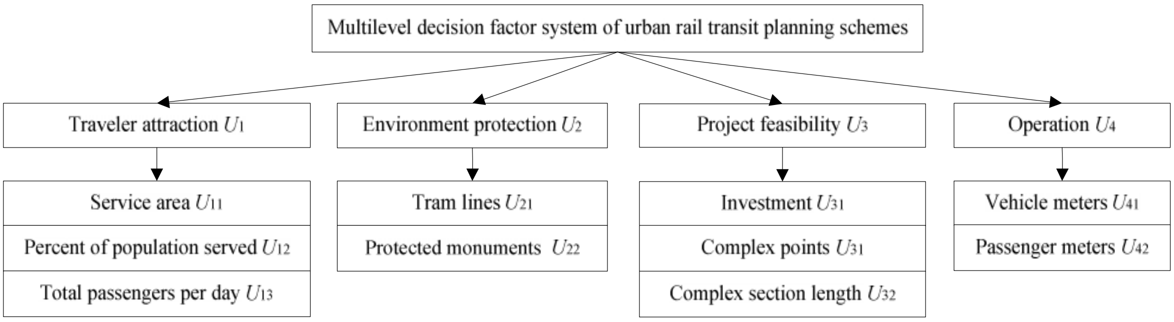


Fig. 1 Multilevel decision factor system of urban rail transit planning schemes

Of these four objectives, 1) traveler attraction is chose because attracting urban residents to travel by rail transit as much as possible is one of the most important objectives for local authorities in developing urban rail transit. Three sub-indicators, i.e. service area (Km^2), percent of population served and total passengers per day (ten thousand) are selected to reflect this objective; 2) Due to the pressures of rapid urban expansion and serious traffic congestion, environment protection has become a common objective on individual, organizational and governmental level. Tram lines have a good potential in restricting the use of private cars especially in the downtown area and protecting the urban environment. So, more or less of the tram lines, together with the protected monuments are selected to reflect the objective of environment protection; 3) The objective of project feasibility is tailored for construction participants, which aims to objectively and rationally uncover the weaknesses and threats as well as the difficulties existing in the alternatives. Investment (hundred million yuan), complex points and complex section length (Km) are chose here to reflect this objective from economic feasibility and technology feasibility of these three alternative planning schemes; and 4) the objective of operation is tailored for the operators of urban rail transit to estimate urban rail transit's overall performance, and two sub-indicators, i.e. vehicle meters (ten thousand VM) and passenger meters (ten thousand PM) are chose to reflect this objective.

From Fig. 1, we can see that the decision factor system of urban rail transit planning schemes obviously displays a hierarchical characteristic, so multilevel fuzzy decision support model are developed in the next section to revolve the multilevel decision-making problem of urban rail transit planning schemes.

III. Model Developed

The decision process of the optimal schemes, on the one hand, is influenced by the scheme itself and government objective guidelines, such as environmental objective and transportation development objective. On the other hand, however, the decision process needs scientific and effective decision methods. Due to the complexity and uncertainty involved in the decision process, a decision maker may sometimes feel more confident using fuzzy judgments than crisp comparisons. The most important aspect is that the degree of impact of the influence factors on the evaluation objective is considered by membership functions in fuzzy set theory, and this is more reasonable than the other traditional evaluation methods. Therefore, fuzzy comprehensive evaluation based on fuzzy set theory is proposed as a decision-making method that is particularly useful in multivariable circumstances [5]- [7].

As sated, multivariable influence the decision process of the optimal urban rail planning schemes, as there exist multi-objective in developing urban rail transit and each objective influenced by more than one sub-indictor. A multilevel fuzzy comprehensive evaluation is therefore needed when there are many variables affect the evaluation process, which is particularly needed in the decision process of optimal urban rail transit planning schemes, as decision result and objectives as well as the objectives' sub-indicators display a characteristic of hierarchical structure.

Definition 1: Given two limited full sets, i.e. the factor set $U=(u_1,...,u_n)$ and the evaluation set $V=(v_1,...,v_m)$, with r_{ij} presenting the grade of membership of factor $u_i, i=1,...n$ aiming at evaluation $v_j, j=1,...,m$, the fuzzy relation between factor set and evaluation set can be described by the evaluation matrix R:

$$R=\begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1m} \\ r_{21} & r_{22} & \cdots & r_{2m} \\ \vdots & \vdots & \vdots & \vdots \\ r_{n1} & r_{n2} & \cdots & r_{nm} \end{bmatrix} \tag{1}$$

where $0 \le r_{ij} \le 1, i=1,...,n, j=1,...,m$.

Definition 2: A is a fuzzy subset of the factor set U, if $B \subseteq V$, then the comprehensive evaluation result B can be defined as follows:

$$B = A \circ R = (b_1,...,b_m) \tag{2}$$

where "$\circ$" represents the fuzzy operator.

The process is called as fuzzy change. Fig. 2 depicts the general process of single-level fuzzy comprehensive evaluation.

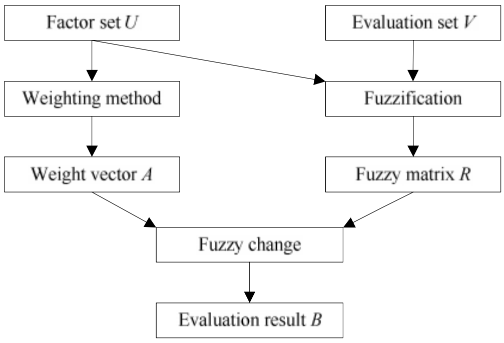


Fig. 2 General process of single-level fuzzy comprehensive evaluation

Definition 3: Let $A=(a_1,...,a_n), 0 \le a_i \le 1, i=1,...,n$ be the weight vector, which is the extent of recognition of factors from valuators. Consistent matrix analysis method [8]-[9] developed from AHP [10] is used in our case to determine the weight vector, which is not displayed in this study. Different definitions of fuzzy operator " $\circ$ " will lead to different fuzzy comprehensive evaluation models. The $M(\cdot, \oplus)$ model [11] is used in our case to get the general computation equation of evaluation vectors:

$$b_j = \min\left(1, \sum_{i=1}^{n} a_i r_{ij}\right), j=1,...,m \quad (3)$$

Definition 4: For a given evaluation, if factor set U is composed of $k, k \ge 2$ layers with the first layer including n factors. The general modality of multilevel fuzzy comprehensive evaluation model is:

$$\underset{\text{Result}}{B} = \underset{\text{First layer}}{A_1 \circ R_1} = A_1 \circ \underset{\text{Second layer}}{\begin{bmatrix} A_{11} \circ R_{11} \\ \vdots \\ A_{1n} \circ R_{1n} \end{bmatrix}} = A_1 \circ \begin{bmatrix} A_{11} \circ \underset{\text{Third layer}}{\begin{bmatrix} A_{111} \circ R_{111} \\ \vdots \\ A_{11p} \circ R_{11p} \end{bmatrix}} \\ \vdots \\ A_{1n} \circ \begin{bmatrix} A_{1n1} \circ R_{1n1} \\ \vdots \\ A_{1nq} \circ R_{1nq} \end{bmatrix} \end{bmatrix} = \cdots\cdots \quad (4)$$

where A_1, A_{1i} and A_{1ij} represent the weight vectors through the first layer to the third layer, R_1, R_{1i} and R_{1ij} represent the evaluation matrices through the first layer to the third layer (take first three levels as an example).

The process of multilevel fuzzy comprehensive evaluation begins with the base layer (layer k), with a stepwise computation that is completed upwards, to the final evaluation result B. The evaluation result of layer k is the very grade of membership of the factor of layer $k-1$.

IV. Decision Process Analysis

Three alternative planning schemes, planned as Scheme 1, Scheme 2 and Scheme 3, are considered as the decision alternatives. The three schemes (please see Table 3 for details), own different service area, different number of tram lines, different passenger meters and so on, are firstly evaluated in framework of the proposed model on the basis of the multilevel decision factor system established for urban rail transit planning schemes (Fig. 1), and then make a choice on the superior urban rail transit scheme.

TABLE I
VALUES OF SUB-INDICATPRS

Sub-indicator	Factor value		
	Scheme 1	Scheme 2	Scheme 3
SA	239	230	228
PPS	0.528	0.592	0.512
TPPD	250	230	230
TL	8	9	12
PM	33	27	29
IN	1660	1550	1450
CP	23	22	22
CSL	79.6	81.4	59.5
VM	21.04	20.93	20.93
PM	1670	1650	1610

SA is the service area; PPS is the percent of population served; TPPD is the total passengers per day; TL is the tram lines; PM is the protected monuments; IN is the investment; CP is the complex points; CSL is the complex section length; VM is the vehicle meters; and PM is the passenger meters

A. Establishment of Factor Set

According to the multi-objectives and their sub-indicators of urban rail transit planning schemes, a multilevel factor set of urban rail transit planning schemes is established as follows:

$$U = \left(U_1 \middle| (U_{11}, U_{12}, U_{13}) \quad U_2 \middle| (U_{21}, U_{22}) \quad U_3 \middle| (U_{31}, U_{32}, U_{33}) \quad U_4 \middle| (U_{41}, U_{42})\right)$$

B. Establishment of Evaluation Set

An evaluation set consists of all evaluation results for the evaluation objective and is usually expressed by fuzzy language. In this study, the evaluation set in our case consists of five linguistic variables:

$$V = (V_1 \ \ V_2 \ \ V_3 \ \ V_4 \ \ V_5) = (\text{Poor General Moderate Good Excellent})$$

Each linguistic variable must be described in detail, and taken as an evaluation criterion of each influence factor.

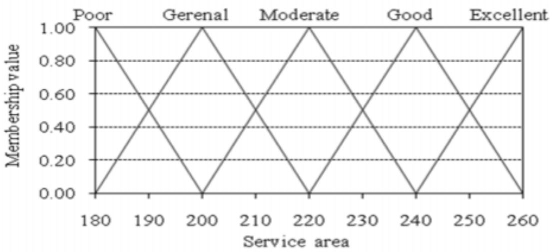
TABLE II
EVALUATION CRITERIA OF SUB-INDICATORS

Sub-indicator	Evaluation criteria				
	Poor	General	Moderate	Good	Excellent
SA	[180,190)	[190,210)	[210,230)	[230,250)	≥250
PPS	[0.50,0.51)	[0.51,0.53)	[0.53,0.56)	[0.56,0.60)	≥0.60
TPPD	[200,205)	[205,215)	[215,235)	[235,265)	≥265
TL	[7,7.25)	[7.25,8.25)	[8.25,10.00)	[10.00,12.50)	≥13.5
PM	[25,26)	[26,28)	[28,32)	[32,36)	≥36
IN	≥1750	[1750,1650)	[1650,1550)	[1550,1450)	[1450,1400)
CP	≥24.75	[24.75,23.5)	[23.5,21.5)	[21.5,20.25)	[20.25,20)
CSL	≥85	[85,75)	[75,65)	[65,55)	[55,50)
VM	[20,20.25)	[20.25,20.75)	[20.75,21.25)	[21.25,21.75)	≥21.75
PM	[1600,1610)	[1610,1630)	[1630,1660)	[1660,1700)	≥1700

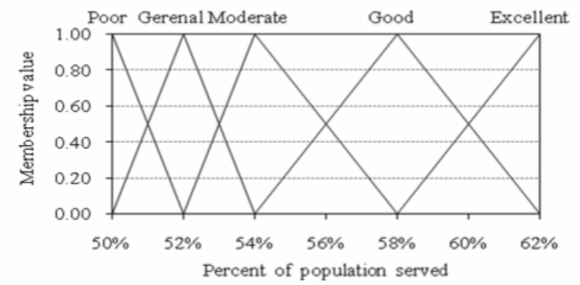
Following discussion with domain experts and based on basic conditions of the alternative projects, the evaluation criteria for sub-indicators are illustrated in Table II.

C. Evaluation Matrix of Sub-indicator

Each sub-indicator such as service area, percent of population served, total passengers per day, etc. considered in the model should be transformed into fuzzy evaluation matrix by fuzzy membership function. The membership functions of ten sub-indicators are defined by triangle distribution in our case for convenience of calculation and extension, as showed in Fig. 3.



(a)



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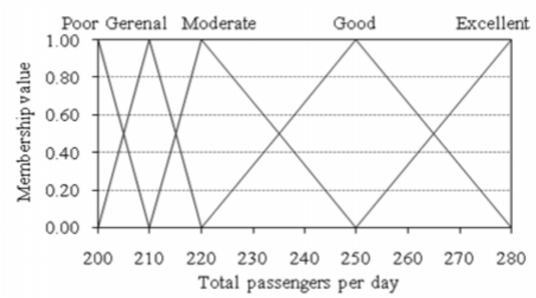

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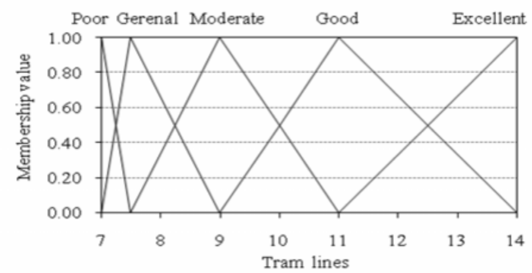

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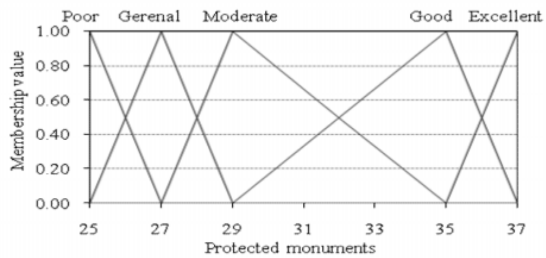

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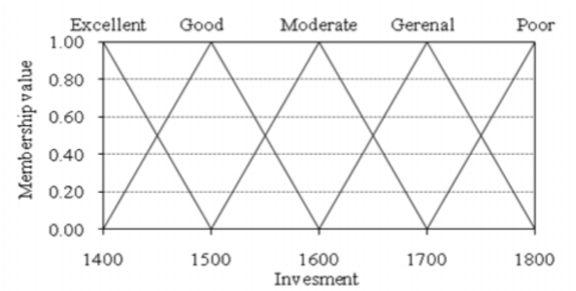

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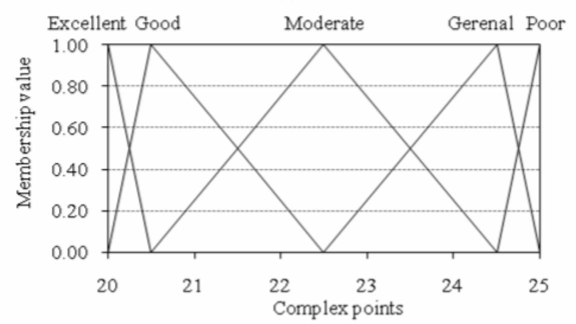

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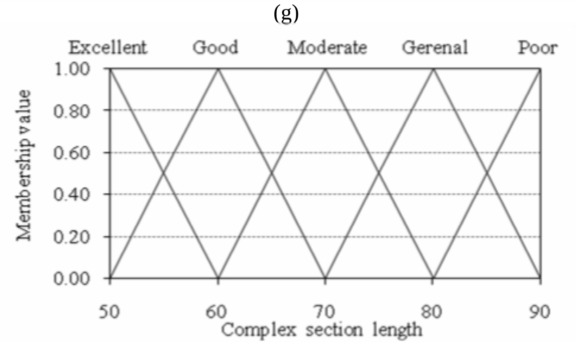

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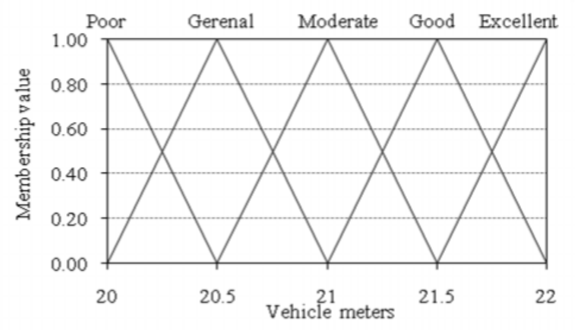
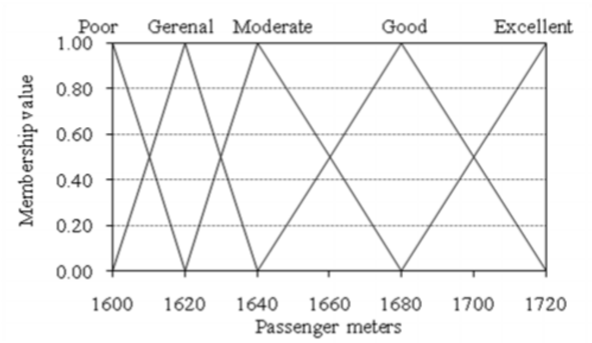


(i)



(j)

Fig. 3 Membership functions of sub-indicators

Membership functions of both factor set and evaluation set make up the evaluation matrix. According to the factor value of three alternative planning schemes listed in Table 1 and the membership functions as shown in Fig. 3, the evaluation matrices of sub-indicators for these three alternative planning schemes are presented as follows:

$$R_{11}^{1}=\begin{bmatrix}\begin{bmatrix}0 & 0 & 0.200 & 0.800 & 0\\ 0 & 0.200 & 0.800 & 0 & 0\\ 0 & 0 & 0 & 1 & 0\end{bmatrix}\\ \begin{bmatrix}0 & 0 & 0.667 & 0.333 & 0\\ 0 & 0 & 0.571 & 0.429 & 0\end{bmatrix}\\ \begin{bmatrix}0 & 0.200 & 0.800 & 0 & 0\\ 0 & 0.920 & 0.080 & 0 & 0\\ 0 & 0.500 & 0.500 & 0 & 0\end{bmatrix}\\ \begin{bmatrix}0 & 0 & 0.840 & 0.160 & 0\\ 0 & 0 & 0.500 & 0.500 & 0\end{bmatrix}\end{bmatrix}$$

$$R_{11}^{2}=\begin{bmatrix}\begin{bmatrix}0 & 0 & 1 & 0 & 0\\ 0 & 0 & 0 & 0.400 & 0.600\\ 0 & 0.333 & 0.667 & 0 & 0\end{bmatrix}\\ \begin{bmatrix}0 & 0 & 1 & 0 & 0\\ 0 & 1 & 0 & 0 & 0\end{bmatrix}\\ \begin{bmatrix}0 & 0 & 1 & 0 & 0\\ 0 & 0 & 0.500 & 0.500 & 0\\ 0.280 & 0.720 & 0 & 0 & 0\end{bmatrix}\\ \begin{bmatrix}0 & 0.280 & 0.720 & 0 & 0\\ 0 & 0 & 0.500 & 0.500 & 0\end{bmatrix}\end{bmatrix}$$

$$R_{11}^{3}=\begin{bmatrix}\begin{bmatrix}0 & 0.200 & 0.800 & 0 & 0\\ 0.800 & 0.200 & 0 & 0 & 0\\ 0 & 0.333 & 0.667 & 0 & 0\end{bmatrix}\\ \begin{bmatrix}0 & 0 & 0 & 0.333 & 0.677\\ 0 & 0 & 1 & 0 & 0\end{bmatrix}\\ \begin{bmatrix}0 & 0 & 0 & 0 & 1\\ 0 & 0 & 0.500 & 0.500 & 0\\ 0 & 0 & 0 & 0.900 & 0.100\end{bmatrix}\\ \begin{bmatrix}0 & 0.280 & 0.720 & 0 & 0\\ 0 & 0 & 0 & 0 & 1\end{bmatrix}\end{bmatrix}$$

where R_{11}^{1} , R_{11}^{2} and R_{11}^{3} respectively stand for the sub-indicators' evaluation matrices of Scheme 1, Scheme 2 and Scheme 3.

D. Weight Vector of Objectives and Their Sub-indicators

Use consistent matrix analysis method developed from AHP to determine the weight vector, the calculation results are showed as follows:

$$\begin{aligned}A&=\left(A_{\mathrm{TA}}\left|\left(A_{\mathrm{TA}}^{1},A_{\mathrm{TA}}^{2},A_{\mathrm{TA}}^{3}\right)\right.\quad A_{\mathrm{EP}}\left|\left(A_{\mathrm{EP}}^{1},A_{\mathrm{EP}}^{2}\right)\right.\quad A_{\mathrm{PF}}\left|\left(A_{\mathrm{PF}}^{1},A_{\mathrm{PF}}^{2},A_{\mathrm{PF}}^{3}\right)\right.\quad A_{\mathrm{OP}}\left|\left(A_{\mathrm{OP}}^{1},A_{\mathrm{OP}}^{2}\right)\right.\right)\\ &=\left(0.4997\left|\left(0.5228\quad 0.3023\quad 0.1749\right)\right.\quad 0.2469\left|\left(0.6667\quad 0.3333\right)\right.\right.\\ &\qquad\left.0.1578\left|\left(0.5006\quad 0.3155\quad 0.1839\right)\right.\quad 0.0955\left|\left(0.5000\quad 0.5000\right)\right.\right)\end{aligned}$$

where A_{TA} , A_{EP} , A_{PF} and A_{OP} respectively stand for the objective's weight of traveler attraction, environment protection, project feasibility and operation, $A_i^j, i\in(\mathrm{TA, EP, PF, OP})$, $j\in(1, 2, 3)$ or $(1, 2)$ are the weights of sub-indicators

E. Evaluation Matrix of Four Objectives

According to Equation (4), the evaluation matrix of four objectives of Scheme 1 is obtained as follows:

$$R_{1}^{1}=A_{11}^{1}\circ R_{11}^{1}=\begin{bmatrix}\begin{bmatrix}0.5228\\0.3023\\0.1749\end{bmatrix}^{T}\circ\begin{bmatrix}0 & 0 & 0.200 & 0.800 & 0\\ 0 & 0.200 & 0.800 & 0 & 0\\ 0 & 0 & 0 & 1 & 0\end{bmatrix}\\ \begin{bmatrix}0.6667\\0.3333\end{bmatrix}^{T}\circ\begin{bmatrix}0 & 0 & 0.667 & 0.333 & 0\\ 0 & 0 & 0.571 & 0.429 & 0\end{bmatrix}\\ \begin{bmatrix}0.5006\\0.3115\\0.1839\end{bmatrix}^{T}\circ\begin{bmatrix}0 & 0.200 & 0.800 & 0 & 0\\ 0 & 0.920 & 0.080 & 0 & 0\\ 0 & 0.500 & 0.500 & 0 & 0\end{bmatrix}\\ \begin{bmatrix}0.5000\\0.5000\end{bmatrix}^{T}\circ\begin{bmatrix}0 & 0 & 0.840 & 0.160 & 0\\ 0 & 0 & 0.500 & 0.500 & 0\end{bmatrix}\end{bmatrix}$$

$$=\begin{bmatrix}0 & 0.0605 & 0.3464 & 0.5931 & 0\\ 0 & 0 & 0.6350 & 0.3650 & 0\\ 0 & 0.4823 & 0.5177 & 0 & 0\\ 0 & 0 & 0.6700 & 0.3300 & 0\end{bmatrix}$$

Similarly, the objectives' evaluation matrices of Scheme 2 and Scheme 3 are obtained as follows:

$$R_{1}^{2}=\begin{bmatrix}0 & 0 & 0.5228 & 0.2958 & 0.1814\\ 0 & 0.333 & 0.6667 & 0 & 0\\ 0.0515 & 0.1324 & 0.6584 & 0.1578 & 0\\ 0 & 0.1400 & 0.6100 & 0.2500 & 0\end{bmatrix}$$

$$R_{1}^{3}=\begin{bmatrix}0.2418 & 0.1650 & 0.4765 & 0.1167 & 0\\ 0 & 0 & 0.3333 & 0.2220 & 0.4447\\ 0 & 0 & 0.1577 & 0.3233 & 0.5190\\ 0 & 0.1400 & 0.3600 & 0 & 0.5000\end{bmatrix}$$

F. Results of Comprehensive Evaluation Matrix

According to Equation (2) and Equation (4), on the basis of the calculated evaluation matrices and weight vector, final comprehensive evaluation matrices are obtained as follows:

$$B^{1}=A_{1}\circ R_{1}^{1}=\begin{bmatrix}0.4997\\0.2469\\0.1578\\0.0995\end{bmatrix}^{T}\times\begin{bmatrix}0 & 0.0605 & 0.3464 & 0.5931 & 0\\ 0 & 0 & 0.6350 & 0.3650 & 0\\ 0 & 0.4823 & 0.5177 & 0 & 0\\ 0 & 0 & 0.6700 & 0.3300 & 0\end{bmatrix}$$

$$=\begin{bmatrix}\overset{\text{Poor}}{0.0000} & \overset{\text{Gerenal}}{0.1063} & \overset{\text{Moderate}}{0.4757} & \overset{\text{Good}}{0.4189} & \overset{\text{Excellent}}{0.0000}\end{bmatrix}$$

$$B^{2}=A_{1}\circ R_{1}^{2}=\begin{bmatrix}\overset{\text{Poor}}{0.0081} & \overset{\text{Gerenal}}{0.1166} & \overset{\text{Moderate}}{0.5880} & \overset{\text{Good}}{0.1966} & \overset{\text{Excellent}}{0.0907}\end{bmatrix}$$

$$B^{3}=A_{1}\circ R_{1}^{3}=\begin{bmatrix}\overset{\text{Poor}}{0.1208} & \overset{\text{Gerenal}}{0.0959} & \overset{\text{Moderate}}{0.3797} & \overset{\text{Good}}{0.1641} & \overset{\text{Excellent}}{0.2395}\end{bmatrix}$$

From the results, it is decided that Scheme 3 is better than Scheme 1 and Scheme 2 since Scheme 3 has outstanding performances in tram lines, monument protection, relatively less investment and construction difficulty, which shows that Scheme 3 could play an important role in environment protection and guarantee the feasibility during the construction progress. It is well known that protecting environment is a major objective in developing urban rail transit, and this objective is particularly important for Suzhou as there exist many classical gardens in its urban area. Suzhou is a popular tourist city and is known for its natural beauty as well as historical sites. Developing urban rail transit, on the one hand, is to satisfy residents' travel demand and promote the development of local tourism as well as other industries. On the other hand, however, economic development should never be at the cost of the environment. To accomplish these objectives, Scheme 3 will play a very important role in Suzhou.

V. CONCLUSION

A multilevel fuzzy decision support model is developed in this paper for selecting the optimal urban rail transit planning schemes in China on the basis of single-level fuzzy comprehensive evaluation model and consistent matrix analysis weighting method. It is found that the proposed model is useful in multivariable circumstances particularly when these decision variables display a characteristic of hierarchical distribution. Real-case study indicates that the proposed model particularly useful in identifying the superior urban rail transit planning scheme, which can be used as an efficiently decision method by decision makers.

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