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FUZZY MULTIOBJECTIVE DECISION SUPPORT MODEL FOR URBAN RAIL TRANSIT PROJECTS IN CHINA

Jinbao Zhao, Wei Deng
School of Transportation, Southeast University, Si Pai Lou #2, Nanjing 210096, China

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Abstract. This paper aims at developing a fuzzy multiobjective decision support model for urban rail transit projects 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 is developed. To do so, detailed description and definition of multilevel fuzzy comprehensive evaluation is displayed. In the decision process, the followings are considered as the influential objectives: traveller attraction, environment protection, project feasibility and operation. In addition, consistent matrix analysis method is used to determine the weights between objectives and the factor weights between factors, which reduce the work caused by repeated establishment of the decision matrix on the basis of ensuring the consistency of decision matrix. An application study is provided as an example to demonstrate the feasibility of this model. The results show that this model is reliable and applicable for decisionmaking in urban rail transit projects. Finally, a decision support system is developed to benefit decisionmakers in optimizing the process of identifying superior urban rail transit projects.

Keywords: urban rail transit; multiobjective decision support model; multilevel fuzzy comprehensive evaluation; consistent matrix analysis; AHP method; fuzzy.

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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, and so on, had constructed rail transit lines totaling up to 1395 km with 48 lines under operation (National Bureau of Statistics of China 2011). There are another 28 cities, including Suzhou, Wuhan, Xi'an, and so on, which have been approved by China's State Council, and are planning or constructing rail transit projects. By 2015, China plans to construct 96 rail transit lines. The total mileage will be 2550 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.

With such a large-scale rail transit construction in China, how to choose the optimal rail transit alternatives for cities is a critical problem at present. In the rapid development phases of urban rail transit, decisions have to be taken under time pressure and stress, which easily result in informal and intuitive decisions. In principle, before building urban rail transit, alternative projects should be planned and designed, which allow decisionmakers to execute the evaluation procedures, which are judged appropriately to ensure the smoothness of construction process and healthy development

Corresponding author: Jinbao Zhao
E-mail: jinbaozhao@seu.edu.cn

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of urban transportation, as well as improve urban transit's performance and peoples' living standards. Whether the optimal rail transit project could win or not, an effective decision is of vital importance.

Researchers have done hard work dealing with the problem of selecting optimal urban rail transit projects in China. They made comparisons on the alternatives and decided optimal projects on the basis of different evaluation methods, that is, AHP-TOPSIS selection method (Li, Wu 2007), fuzzy expandable engineering method (Li, Zhang 2009), grey relation method (Zhang, Qin 2010), and so on. 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. Urban Mass Transportation Administration (UMTA) utilized Cost-Effectiveness Analysis (CEA) to evaluate the alternative rail transit projects, and made detailed assessment of complex project alternatives in several technical aspects (Urban Mass Transportation Administration 1986). Although Horn (1981) has questioned CEA after analysing the indicators in nine developed mega-cities worldwide, CEA is still the strongest at the federal level in the US. Furthermore, any kind of technical evaluation faces an uphill struggle in the decision process. For example, CEA is used frequently at the federal level in the US, but states and localities, to a lesser extent, accept the appropriateness of this format while not necessarily doing a lot of it. Local authorities may simply utilize process-oriented techniques, such as benefit–cost analysis (DeCorla-Souza *et al.* 1997; Lee 2000), Delphi method (Spinelli 1983; Okoli, Pawlowski 2004), multicriteria programming (Dyson 1980; Pohekar, Ramachandran 2004; Mendoza, Martins 2006) and so on, to decide an optimal rail transit project.

With consideration of complexities compounded by the unique characteristics of Chinese economics, culture, slow progress of passing construction law and regulations and the bureaucracy in China construction industry, explicit development objectives should be determined in the decisionmaking process of Chinese managers to choose optimal urban rail transit projects. This study emphasizes on developing a multiobjective decision support model for China's local authorities to support their decision-making skills in urban rail transit planning and development in integrating the Chinese context. Traveller attraction, environmental protection, project feasibility and operation are identified in the decision-making model of urban rail transit projects choice. The development process of the proposed model is given in Fig. 1. Multilevel fuzzy comprehensive evaluation is used to validly reflect the hierarchical characteristic of screening alternative urban rail transit projects. In the proposed model,

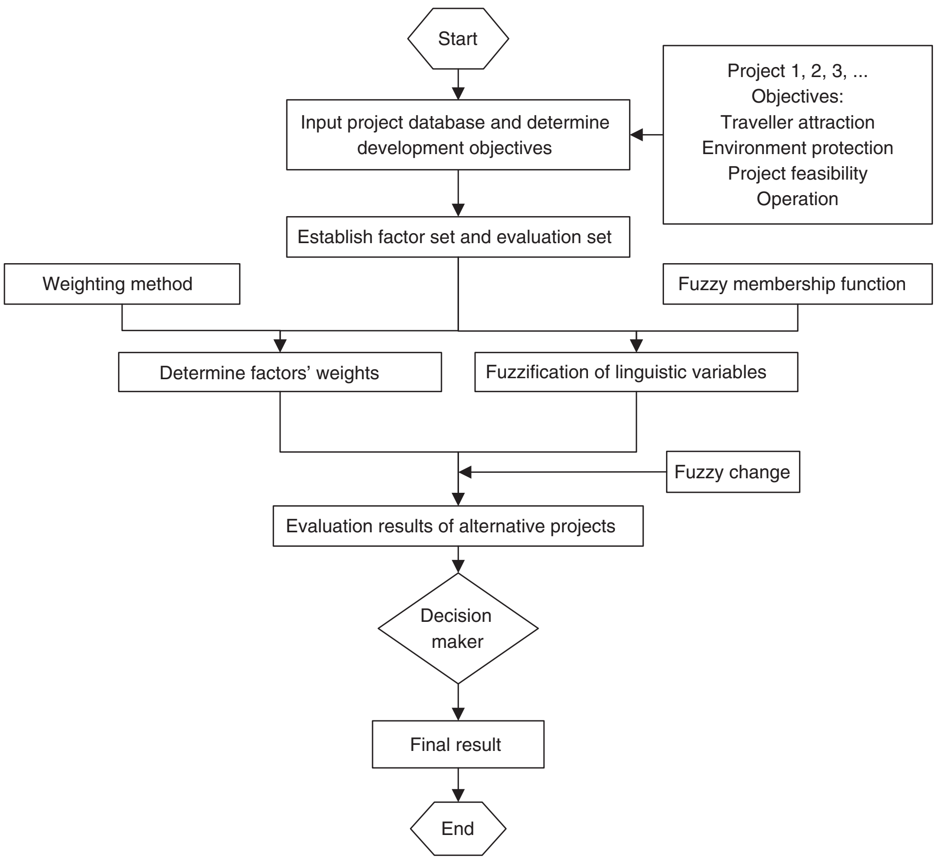

Fig. 1. Development process of the proposed model

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 performance of the model was accurately described and evaluated by a real-case study with three alternatives located in Suzhou. Moreover, a framework of decision support system is developed to optimize the process of identifying superior alternatives.

1. Model developed

The decision process of the optimal project, on the one hand, is influenced by the project 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 judgements 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 (Karsak, Tolga 2001; Sheng *et al.* 2008; Lam *et al.* 2009).

Multivariable circumstances influence the decision process of the optimal urban rail transit projects, as there exist multiobjective ones in developing urban rail transit, and each objective is influenced by more than one factor. A multilevel fuzzy comprehensive evaluation is therefore needed when there are many variables affecting the evaluation process, which is particularly appropriate in the decision process of optimal urban rail transit projects, as decision result and objective, as well as influence factor display the characteristic of hierarchical structure in our case.

1.1. General description

Definition 1. Given two limited full sets, that is, the factor set $U=(u_1,\dots,u_n)$ and the evaluation set $V=(v_1,\dots,v_m)$, with r_{ij} presenting the grade of membership of factor u_i, $i=1,\dots n$ aiming at evaluation v_j, $j=1,\dots,m$, 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: $0 \le r_{ij} \le 1$, $i=1,\dots n$, $j=1,\dots m$.

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:

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

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.

Definition 3. Let $A=(a_1,\dots,a_n)$, $0 \le a_i \le 1$, $i=1,\dots,n$ be the weight vector, which is the extent of recognition of factors from valuators. Different definitions of fuzzy operator '$\circ$' will lead to different fuzzy comprehensive evaluation models. The M $(\bullet,\oplus)$ model (Li, Shen 2006) is used in our case to get the general computation equation of evaluation vectors:

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

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 multi-level fuzzy comprehensive evaluation model is:

$$\overset{\boxed{\text{Result}}}{B}=\overset{\boxed{\text{First layer}}}{A_1\circ R_1}=A_1\circ\overset{\boxed{\text{Second layer}}}{\begin{bmatrix} A_{11}\circ R_{11} \\ \vdots \\ A_{1n}\circ R_{1n}\end{bmatrix}}= \\ A_1\circ\begin{bmatrix} A_{11}\circ\overset{\boxed{\text{Third layer}}}{\begin{bmatrix} A_{111}\circ R_{111} \\ \vdots \\ A_{11p}\circ R_{11p}\end{bmatrix}} \\ \vdots \\ A_{1n}\circ\begin{bmatrix} A_{1n1}\circ R_{1n1} \\ \vdots \\ A_{1nq}\circ R_{1nq}\end{bmatrix}\end{bmatrix}=\cdots\cdots, \tag{4}$$

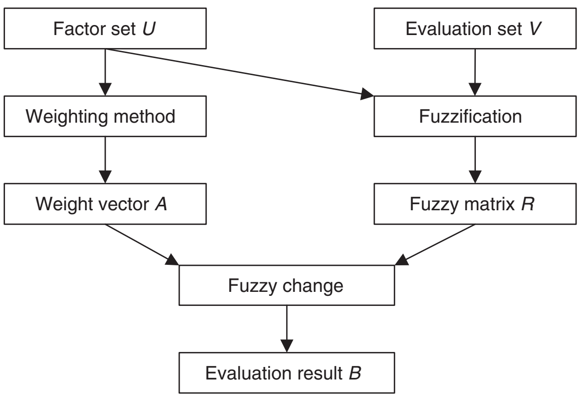

Fig. 2. General process of a single-level fuzzy comprehensive evaluation

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 $k-1$.

1.2. Consistent matrix analysis method

AHP was first proposed by Saaty (1980), which divides various factors of a complex problem into orderly interrelated levels, and makes the problem methodize. Based on a certain subjective judgements structure of objective, expert advice and objective judgement of analysis are combined directly and effectively.

Consistency check is required in traditional AHP method. Much more workloads are caused by repeated establishment of the decision matrix. In order to avoid the additional workload, consistent matrix analysis method (Ye *et al.* 2006; Zheng *et al.* 2010) is introduced as follows:

– ***Step 1:*** Establish decision matrix.

$$A = \left(a_{ij}\right)_{n\times n}, \tag{5}$$

where: $a_{ij} = 1 (i = j)$, $a_{ji} = 1/a_{ij}$.
The 9-scale linguistic variables to compare the relative importance between any two dimensions are used. The linguistic variables to describe the importance comparison are shown in Table 1.

– ***Step 2:*** Order.

$$b_{ij} = \sqrt[n]{\prod\nolimits_{k=1}^{n} a_{ik} \cdot a_{kj}} \tag{6}$$

and the consistent matrix is:

$$B = \left(b_{ij}\right)_{n\times n}, \tag{7}$$

where: $b_{ij} = 1 (i = j)$, $b_{ji} = 1/b_{ij}$, $b_{ij} = b_{ik} \cdot b_{kj}$.

– ***Step 3:*** Calculate the weight:

$$w_i = \frac{c_i}{\sum_{k=1}^{n} c_k}, i = 1, 2, ..., n, \tag{8}$$

where: $c_i = \sqrt[n]{\prod_{k=1}^{n} b_{ik}}$, $i = 1, 2, \ldots, n$.

From above, consistent matrix analysis method can not only reduce the work caused by repeated establishment of the decision matrix, but can also ensure the consistency of the decision matrix. Thus, the process of determining the weights can be simplified.

In order to obtain subjective weights, the decision group is asked to make pair-wise comparison for the elements at a given level with the same above factor according to Table 1.

Table 1. Comparison of relative importance of factors

Scale of relative importance	Linguistic variable	Comparative judgement
1	equally important	u_i and u_j are equally important
3	weakly important	u_I is weakly more important than u_j
5	essentially important	u_I is essentially more important than u_j
7	very strongly important	u_I is very strongly more important than u_j
9	absolutely important	u_I is absolutely more important than u_j
2, 4, 6, 8 is an intermediate scale		

2. Multiobjective of urban rail transit and considered factors

Under the planned economy, construction activities including the urban rail transit projects in China are planned to meet the anticipated objectives. Profit making was not a major goal for any cities in the development of urban rail transit. Many cities in China presently confront with traffic congestion challenges, and they have to adjust the compositions of traffic infrastructures to increase the attraction of urban transit. Furthermore, urban rail transit has its own characteristics compared with other travel modes. Different cities may have different goals, but cherish some common objectives in developing urban rail transit. Travellers' attraction, environment protection, project feasibility and operation are closely related to most cities' objectives in China. Therefore, this paper emphasizes on these four objectives and makes a detailed introduction to them.

2.1. Travellers' attraction

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. The primary factors affecting travellers' attraction that decisionmakers have to consider in a rail transit project are:

– *Service area:* an effective factor of the attraction of rail transit from its potential market. Obviously, one important consideration here is the definition of 'service area'. Different definitions of service area will lead to different calculating results. In our case, we have defined it on the basis of line types and the serviced places. The service radius of tram station is 600 m in urban area, while the radius of subway station is 750 m in urban area, and 1,000 m in suburban district.

- *Percent of population served:* the proportion of the service area population that has access to rail transit service. This indicator also has a potential dependence on the definition of the service area. It measures whether someone is near rail transit service, not how good that service is.
- *Total passengers per day:* this is an indicator of the level of passenger use of urban rail transit in service, which can reflect the system patronage and capacity utilization indexed to an average operation day. It is influenced not only by total passenger demand but also by system capacity, length of operating day, length of route, average distance travelled per passenger, and the extent to which demand varies between peak and off-peak periods, and so on.

2.2. Environment protection

Due to the pressures of rapid urban expansion and serious traffic congestion, environment protection has become a common objective at the individual, organizational and governmental level. Developing urban rail transit has a huge potential in protecting environment, as each person who chooses to travel by rail transit contributes to a cleaner environment. The factors being considered in environmental protection include:

- *Tram lines:* steel wheels on steel track create much less friction than rubber tyres on bitumen, thus creating dramatically less pollution when carrying the same load. Furthermore, tram lines can occupy urban space at ground-level and restrict the use of private cars especially in the downtown area. Thus, more or less, tram lines in the urban rail transit alternatives are considered as an important factor for environment protection.
- *Protected monuments:* many cities firstly develop urban rail transit in the main urban area or old town area as they have a relatively higher population density than other places, but the old town area usually has many monuments and attractions, which should be protected meticulously. The number of protected monuments in urban rail transit also is considered in our case as an important factor reflecting environment protection efforts.

2.3. Project feasibility

This objective 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. In China, the difficulties before many local authorities in developing urban rail transit mainly include capital shortage and technology breakthrough, that is, economic feasibility and technology feasibility, which can be reflected from the following three factors:

- *Investment:* developing urban rail transit needs huge investment on infrastructure construction, equipment purchase and vehicle operation. Cost saving is a common objective for many cities in developing urban rail transit in China.
- *Complex points:* in order to estimate whether the projects proceed smoothly or not, the total number of complex points in alternatives should be researched in advance. The less the number of difficult points in an alternative, the more possible participating constructions will trend to it.
- *Complex section length:* different complex points have different complex lengths, so the total complex section length should also be estimated in advance and considered as a factor which affects the construction objective.

2.4. Operation

Before being put into construction, assessing the efficiency and effectiveness of urban rail transit is a major objective for its possible operators. Furthermore, evaluating operating information has an important significance for estimating urban rail transit's overall performance. The following two factors, which combine some aspect of efficiency with some aspect of effectiveness in a single indicator, are considered here:

- *Vehicle metres:* total number of metres that operating vehicles of alternatives are driven per day is an important factor to reflect the operation efficiency and effectiveness of urban rail transit, which takes into account total rail vehicles and operating metres. The estimating of vehicle metres also holds potential for operating expense.
- *Passenger's metres:* an accurate factor of service consumed. Passenger's metres provide an indication of average vehicle occupancy and trip distance, and are therefore, highly significant for understanding vehicle utilization and service consumption.

2.5. Relative importance of objectives

Consistency matrix analysis method was used to calculate weights of these four objectives. Based on detailed discussion, pair-wise decision matrix at a given level was made by the decision group. The pair-wise decision matrix and its corresponding consistency matrix calculated by equations (6) and (7) were given in Table 2, and the final calculating weights of these four objectives were also listed in Table 2.

Table 2. Decision matrix, consistent matrix and weights of objectives

	Decision matrix				Consistent matrix					
	TA	EP	PF	OP	TA	EP	PF	OP	c_i	Weight
TA	1	3	3	4	1	2.06	3.224	5.045	2.406	0.4997
EP	1/3	1	2	3	0.485	1	1.565	2.632	1.189	0.2469
PF	1/3	1/2	1	2	0.31	0.639	1	1.682	0.760	0.1578
OP	1/4	1/3	1/2	1	0.198	0.38	0.595	1	0.460	0.0955

Abbreviations: TA – traveller attraction; EP – environment protection; PF – project feasibility; OP – operation.

3. Case study

A large urban rail transit project located in Suzhou with three alternatives was examined to describe accurately the operation process of the fuzzy multiobjective decision support model, and stimulate the necessary concern on multiobjective decision for urban rail transit projects. The three projects (Fig. 3), own different service area, different number of tram lines, different passenger's metres and so on, were evaluated in objectives of traveller's attraction, environment protection, project feasibility and operation concern.

3.1. Establishment of factor set

According to the multiobjective of urban rail transit and their considered factors, a multilevel decision factor system was established as shown in Fig. 4.

On the basis of Fig. 4, the multilevel factor set of urban rail transit projects was established as follows:

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

Table 3 listed the overall ten basic layer factors and their actual value. In order to save paper space, the factors' weights calculated by consistent matrix analysis method were also listed in Table 3.

3.2. 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. Following discussion with domain experts and based on basic conditions of the alternative projects, the evaluation criteria for each basic layer factor were illustrated in Table 4.

3.3. Evaluation matrix of basic layer factor

Each basic layer factor, such as service area, percent of population served, total passengers per day, and so on, considered in the model was transformed into fuzzy evaluation matrix by fuzzy membership functions. The membership functions of ten basic layer factors were defined by triangular distribution in our case, for convenience of calculation and extension, as shown in Fig. 5.

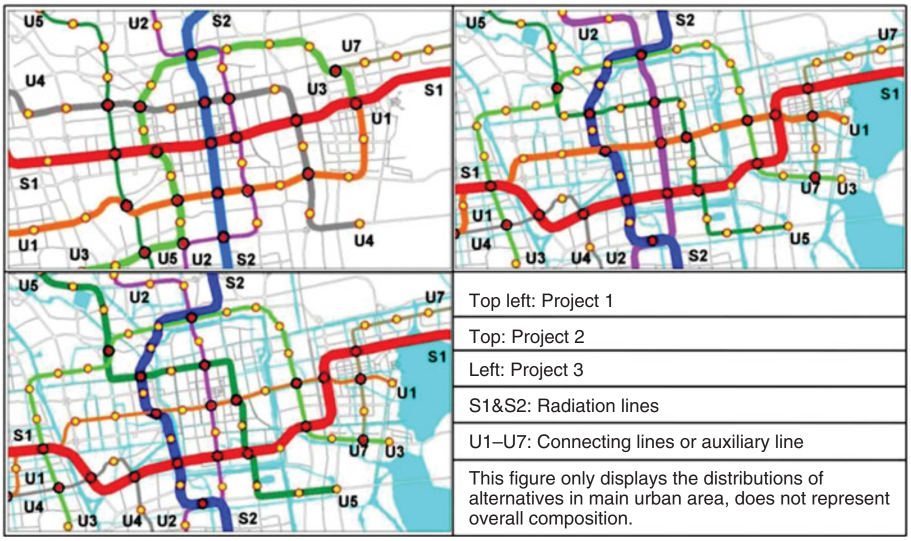

Fig. 3. Layout of three alternative projects in Suzhou's main urban area

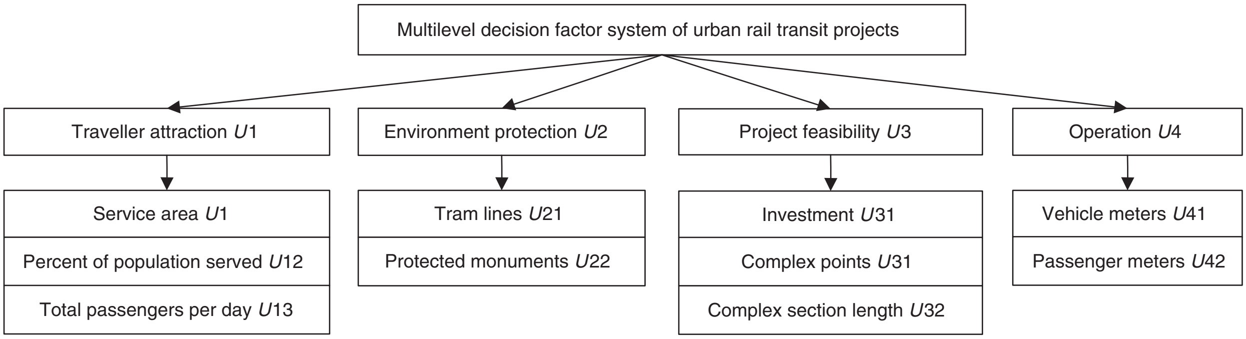

Fig. 4. Multilevel decision factor system of urban rail transit projects

Membership functions of both factor set and evaluation set make up the evaluation matrix. According to the factor value of three alternative projects listed in Table 3, and the membership functions as shown in Fig. 5, the evaluation matrices of basic layer factors for these three alternative projects were represented 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 basic layer factors' evaluation matrices of Project 1, Project 2 and Project 3.

3.4. Weight vector of objective and basic layer factor

According to the calculated weights between objectives (listed in Table 2) and the factor weights between factors (listed in Table 3), the multilevel weight vector was obtained as follows:

$$A=\left(A_{\mathrm{TA}}\middle|\left(A_{\mathrm{TA}}^{1},A_{\mathrm{TA}}^{2},A_{\mathrm{TA}}^{3}\right)A_{\mathrm{EP}}\middle|\left(A_{\mathrm{EP}}^{1},A_{\mathrm{EP}}^{2}\right)\right.$$
$$\left.A_{\mathrm{PF}}\middle|\left(A_{\mathrm{PF}}^{1},A_{\mathrm{PF}}^{2},A_{\mathrm{PF}}^{3}\right)A_{\mathrm{OP}}\middle|\left(A_{\mathrm{OP}}^{1},A_{\mathrm{OP}}^{2}\right)\right)=$$

$$\begin{aligned}&(0.4997|(0.5228\quad 0.3023\quad 0.1749)\\&0.2469|(0.6667\quad 0.3333)\\&0.1578|(0.5006\quad 0.3155\quad 0.1839)\\&0.0955|(0.5000\quad 0.5000)),\end{aligned}$$

where: A_{TA}, A_{EP}, A_{PF} and A_{OP} respectively stand for the objective's weight of traveller's attraction, environment protection, project feasibility and operation, $A_i^j, i\in(\mathrm{TA},\mathrm{EP},\mathrm{PF},\mathrm{OP})$, $j\in(1,\ 2,\ 3)$ or $(1,\ 2)$ is the basic layer factor weights.

3.5. Evaluation matrix of objective

According to equation (4), Project 1's evaluation matrix of objective (first layer factor) was obtained as follows:

$$R_1^1=A_{11}^1\circ R_{11}^1=$$

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

Table 3. Values and weights of the basic layer factors

Basic layer factor	Factor value			Weight
	Project 1	Project 2	Project 3	
Service area (km^2)	239	230	228	0.5228
Percent of population served	0.528	0.592	0.512	0.3023
Total passengers per day (ten thousand)	250	230	230	0.1749
Tram lines	8	9	12	0.6667
Protected monuments	33	27	29	0.3333
Investment (hundred million yuan)	1660	1550	1450	0.5006
Complex points	23	22	22	0.3155
Complex section length (km)	79.6	81.4	59.5	0.1839
Vehicle metres (ten thousand VM)	21.04	20.93	20.93	0.5000
Passenger metres (ten thousand PM)	1670	1650	1610	0.5000

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

Similarly, the objective evaluation matrix of Project 2 and Project 3 were obtained as follows:

$$R_1^2 = \begin{bmatrix} 0 & 0 & 0.5228 & 0.2958 & 0.1814 \\ 0 & 0.333 & 0.6667 & 0 & 0 \\ 0.0515 & 0.1324 & 0.6584 & 0.1578 & 0 \\ 0 & 0.1400 & 0.6100 & 0.2500 & 0 \end{bmatrix};$$

$$R_1^3 = \begin{bmatrix} 0.2418 & 0.1650 & 0.4765 & 0.1167 & 0 \\ 0 & 0 & 0.3333 & 0.2220 & 0.4447 \\ 0 & 0 & 0.1577 & 0.3233 & 0.5190 \\ 0 & 0.1400 & 0.3600 & 0 & 0.5000 \end{bmatrix}.$$

3.6. Results of comprehensive evaluation matrix

According to equations (2) and (4), on the basis of the calculated evaluation matrixes and weights, final comprehensive evaluation matrixes are obtained as follows:

$$B^1 = A_1 \circ R_1^1 =$$

Table 4. Evaluation criteria of the basic layer factors

Basic layer factor	Evaluation criteria				
	Poor	General	Moderate	Good	Excellent
Service area	[180,190)	[190,210)	[210,230)	[230,250)	≥ 250
Percent of population served	[0.50,0.51)	[0.51,0.53)	[0.53,0.56)	[0.56,0.60)	≥ 0.60
Total passengers per day	[200,205)	[205,215)	[215,235)	[235,265)	≥ 265
Tram lines	[7,7.25)	[7.25,8.25)	[8.25,10.00)	[10.00,12.50)	≥ 13.5
Protected monuments	[25,26)	[26,28)	[28,32)	[32,36)	≥ 36
Investment	≥ 1750	[1750,1650)	[1650,1550)	[1550,1450)	[1450,1400)
Complex points	≥ 24.75	[24.75,23.5)	[23.5,21.5)	[21.5,20.25)	[20.25,20)
Complex section length	≥ 85	[85,75)	[75,65)	[65,55)	[55,50)
Vehicle metres	[20,20.25)	[20.25,20.75)	[20.75,21.25)	[21.25,21.75)	≥ 21.75
Passenger metres	[1600,1610)	[1610,1630)	[1630,1660)	[1660,1700)	≥ 1700

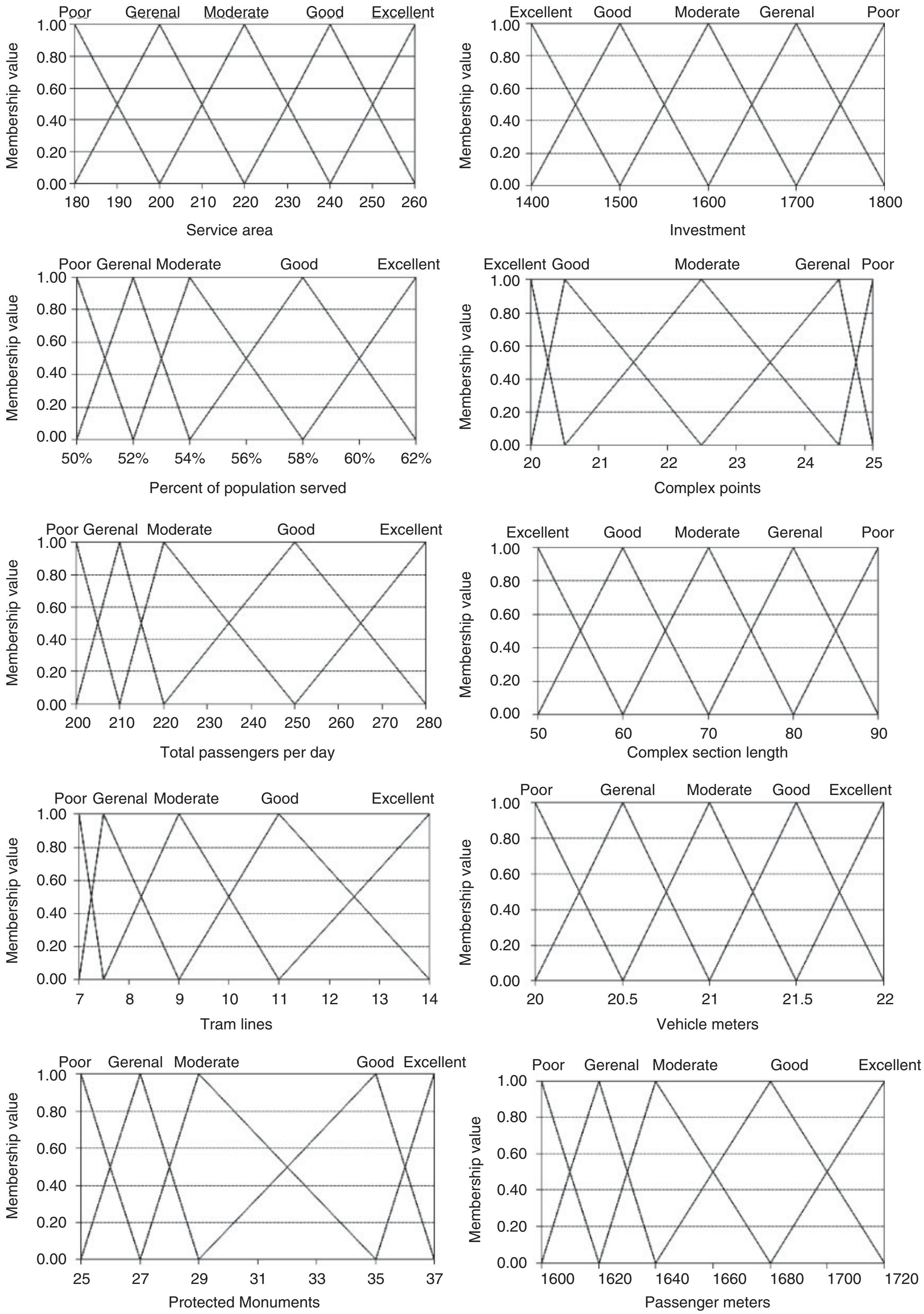

Fig. 5. Membership functions of the basic layer factors

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

$$\begin{bmatrix} \text{Poor} & \text{General} & \text{Moderate} & \text{Good} & \text{Excellent} \\ 0.0000 & 0.1063 & 0.4757 & 0.4189 & 0.0000 \end{bmatrix};$$

$$B^2 = A_1 \circ R_1^2 =$$

$$\begin{bmatrix} \text{Poor} & \text{General} & \text{Moderate} & \text{Good} & \text{Excellent} \\ 0.0081 & 0.1166 & 0.5880 & 0.1966 & 0.0907 \end{bmatrix};$$

$$B^3 = A_1 \circ R_1^3 =$$

$$\begin{bmatrix} \text{Poor} & \text{General} & \text{Moderate} & \text{Good} & \text{Excellent} \\ 0.1208 & 0.0959 & 0.3797 & 0.1641 & 0.2395 \end{bmatrix}.$$

From the results, it is decided that Project 3 is better than Project 1 and Project 2, since Project 3 has outstanding performances in tram lines, monument protection, relatively less investment and construction difficulty, which shows that Project 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, Project 3 will play a very important role in Suzhou.

4. Design of decision support system

In the early phases of an urban rail transit project, decisions have to be taken under the time pressure and stress. Decision-makers may consider objectives, such as development requirement, environment protection and so on. However, if they informally and intuitively try to identify the optimal project, they may come up with poor options. Support is therefore needed to ensure that superior and feasible alternatives are considered for evaluation.

We have developed a decision support system to optimize the process of identifying superior alternatives, which also can be a guideline for devising decision support software for urban rail transit projects in China. Fig. 6 constructs the framework of the decision support system and illustrates the interactions expected and supported with experts and decision-makers.

With the help of this decision support system, some informal decisions can be avoided and high efficiency can be gained. In the decision support system, not only mathematics operation can be realized, but also two important functions, that is, database management and analysis report of decision process.

Database management includes expert database, factor classification, historical factor value and typical case database management. Experts can be selected from the expert database for discussing the multiobjective of developing urban rail transit, calculating the relative importance of objectives and factors, and determining appropriate fuzzy membership function for the fuzzification of factor set and evaluation set.

Factor classification and historical value database is a standard factor database, based on urban rail transit planning, sustainable development of urban transportation and the experience of rail transit construction, and so on. Because the evaluation factors lead directly to the selection of project

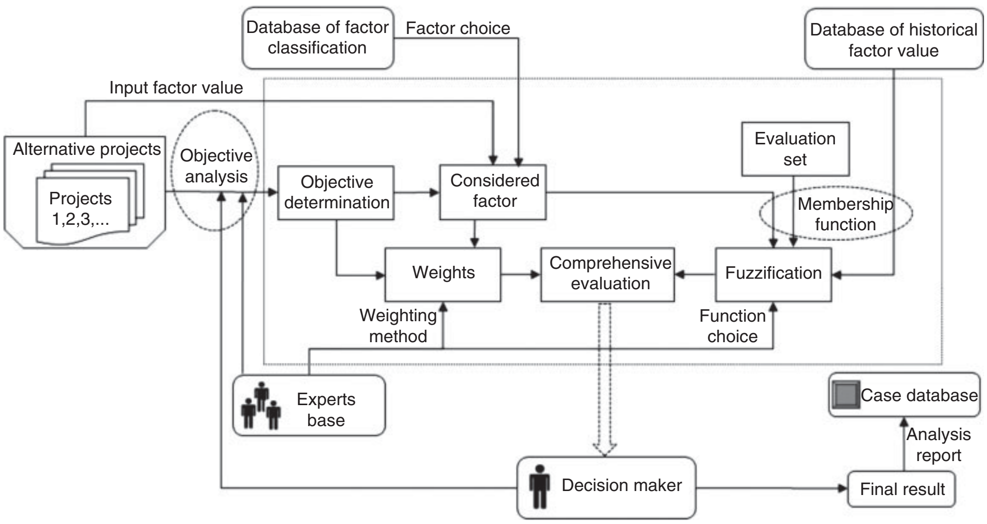

Fig. 6. Decision support system for urban rail transit projects

and development of urban rail transit, with the advancement of human society and the development of urban transportation, the factors in the database should be adjusted dynamically. Such a database should play a guiding role for China's urban rail transit.

Case project database management collects cases of alternative projects domestically and abroad, and evaluates them based on the model presented in this paper. The evaluation results and their actual implementation processes are then compared to test the reliability of the model. By comparison, valuable information related to urban rail transit planning and construction can be obtained.

An analysis report of decision process produces a full record of the operation process and loads it into the case database for future reference.

Conclusions

1) This paper developed a fuzzy multiobjective decision support model for urban rail transit projects in China, on the basis of multilevel fuzzy comprehensive evaluation method improved from the single-level fuzzy comprehensive evaluation model. It is found that this is useful in multivariable circumstances particularly, when these decision variables display a characteristic of hierarchical distribution. Consistent matrix analysis method was used to determine the weights between objectives and the factor weights between factors involved in the proposed model, which not only reduced the work caused by repeated establishment of the decision matrix, but can also, ensure the consistency of the decision matrix.
2) A real-case study is given to illustrate the practicality of the proposed model, which indicates that the proposed model can be used to provide some help to decisionmakers in the decision process of choosing the optimal urban rail transit project in China and other countries. Furthermore, decision support system was developed to benefit decision-makers in optimizing the process of identifying superior alternatives, as well as serves as a guideline for devising decision support software for urban rail transit projects in China and other countries.

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