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Performance evaluation and alternative optimization model of light rail transit network projects: A real case perspective

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Abstract

Light rail transit network is essential to the development of urban public transportation, and this study is aimed to provide a scientific, efficient and new methodology to measure and assess the pros and cons of various planning schemes for light rail transit (LRT) network, which can help guide the process of alternative prioritization and decision-making support. More

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specifically, through establishing the multi-attribute assessment index system, and pondering the combinational weighting model (consistent matrix analysis and information entropy methods), a data-driven and flexible multi-criteria matter-element decision-making (MCMEDM) model for LRT network optimization is constructed in this work. Furthermore, objectivity, impartiality, rationality and validity of the proposed model are discussed and verified by a didactical case with real datasets in Jining, China. The modeling analysis (quantitative procedures) results and findings reveal that this approach is reliable and applicable to appraise and prioritize the LRT networks, avoiding the decision biases due to human or other factors. Additionally, the proposed framework can offer urban planners, managers, decision and policy makers the appropriate comments and suggestions of identifying the superior alternative (project), as well as serve as a guideline or reference for other cities.

Keywords: *traffic engineering, urban rail transit planning, multi-criteria decision-making support, matter-element analysis model, data driven, optimal design*

1. Introduction

The traffic network not only affects the spatial distribution of urban land, but also influences the traffic demand forecasting significantly. With steady improvements of the level of urbanization and motorization, transit-oriented development (TOD) strategy, an effective mode of coordinating urban transportation and land use, has already attracted much attention/expectation and achieved successful practice in many countries around the world

(Cervero 2013; Noland et al. 2017; Singha et al. 2017). A suitable light rail transit (LRT) network planning (a vital part of urban public transit priority) will be capable of prompting the modal transformation of urban transport and shifting residents' trips from autos to public transit.

LRT system is the backbone of the urban public transportation system, which has plenty of strengths on capacity, travel delay, operating efficiency, safety, environmental protection and intensive land use (Cao et al. 2014; Huang et al. 2017). Many cities have recently built or approved this system to combat congestion, sprawl, pollution and to generate considerable or substantial ridership, coaxing drivers out of their cars. In addition, the LRT is faster and more appealing than buses and yet cheaper to build than the heavy rail.

The optimization and decision support of LRT networks are the prerequisite and notable problem before the actual construction and development of rail transit. Excogitation of LRT network schemes is a large-scale complicated system engineering, whose status often controls the overall layout of concrete project and becomes the key and pivotal link during performance evaluating. This whole technological processing needs to be closely connected with the growth of the social economy, population and traffic demand. Present literature and some correlative researches have concentrated on decision-making, evaluation and prioritization of LRT plans and striven hard to carry out respectable investigations and surveys. As the elementary and widely-applicable approaches, cost-effectiveness analysis (CEA) and cost-benefit analysis (CBA or BCA) were utilized to make detailed assessments and screen the alternative rail transit projects from several technical aspects, particularly at the federal or state level in America (Khraibani et al. 2016; Lee 2000; Matute et al. 2015; Mohring 1993; Urban Mass Transportation Administration 1986). In order to manage the rehabilitation and problems of

co-located infrastructure assets, Saad and Hegazy (2017) developed an enhanced benefit-cost analysis (EBCA) optimization method, which proved to be able to arrive at near-optimum funding decisions by achieving an equilibrium state. Similarly, Delphi method and/or fuzzy analytic network process were made great attempts to cope with the related issues (Okoli et al. 2004; Wey et al. 2016). A series of tools, technique for order preference by similarity to an ideal solution (TOPSIS), multiple criteria programming, analytic hierarchy process (AHP) and fuzzy-compositional evaluation model, information entropy theory, had also been developed rapidly and effectively to select the optimum design (Aydin 2017; Gerçek et al. 2004; Jiao 2009; Niyaz et al. 2013; Short et al. 2005). Given this, we can delineate that modeling analysis (quantitative discussion) for the decision course and performance appraisal of LRT network planning should be prominently critical and worth considering.

Beyond that, the usage of other approaches for decision-making and assessment is also relatively widespread and common. Mendoza and Martins (2006) reviewed the traditional multi-criteria decision analysis (MCDA) and new MCDA modeling paradigms, aiming at coping with the forest and other natural resources management planning. Besides, a model combining fuzzy AHP and TOPSIS was proposed to appraise and optimize the fitness of alternative right-of-way corridors to accommodate high-speed intercity passenger rail operations in Texas (Madanu et al. 2015). The performance attributes and indexes impacting European transit systems operating in vastly different monitoring environments were explored via data envelopment analysis (DEA) model (Tsamboulas 2006). However, both advantages and disadvantages exist in these evaluation methods more or less. The complex and sometimes nonlinear relationships of multiple variables in principal component analysis (PCA) would

make statistical models unsuitable and complicated; likewise, the computed results of DEA could be affected by model specification and inclusion/exclusion (input-output) of variables (Andrejić et al. 2013; Omrani et al. 2015; Wanke et al. 2016). Despite that the comprehensive fuzzy technique objectively reflected the real condition at certain points (Sayers et al. 2003), it lost some useful information and emphasized the role of extreme values. Accordingly, both subjective and objective dimensions should be concerned substantially for decision-making support in this paper.

Matter-element (ME) extension analysis would be an appropriate solution for dealing with the multi-index evaluation problems in various fields, such as monitoring the health and water quality of a river ecosystem (Chen et al. 2012; Pan et al. 2015), pavement preventive maintenance treatment and the optimal timing of its placement (Li et al. 2010), and inspecting the traffic service status of Xi'an Metro Line 2 (Yang et al. 2012), etc. Combining the ME theory with correlation functions of performance indexes, Meng et al. (2018) took Shanghai railway transit equipment as a case study, and then established a mathematical model for speed trajectory to realize the multi-objective optimization of the non-compatible problem. On the basis of multi-objective integrated weighting theory and the preceding investigations, a data-oriented matter-element decision-making support model is adopted to obtain the optimum planning scheme by comparing the alternatives and the ideal design in this work. The methodology uses the raw data largely in the process of quantitative transformation and overcomes the shortcomings of other decision-making methods that are not precise or flexible enough. It can make this entire prioritization and decision-making process more scientific, rational, effective, valuable and practical.

The remainder of this study includes four additional sections. Section 2 expounds the major methodology of combinational weighting model and MCMEDM analysis. The following section creates an index system of LRT network assessment and optimization. A systematic case study (empirical analysis) is conducted in Section 4, covering the project context, data source, application of the proposed model, results analysis and the discussion. Eventually, Section 5 concludes this paper with a summary of findings, contributions and directions for the future research.

2. Methodological Framework

This section presents the performance evaluation and alternative optimization model in detail and the needed methodology briefly.

2.1 Essential Concepts of ME Analysis

ME analysis, originating from the extension theory, is an emerging cross-field mathematic method that can resolve diverse incompatibilities and ambiguities in the objective world. The ordered combination (ternary group) comprises basic matter N , whose character c is valued as x , i.e., $R = (N, c, x)$ (Cai 1994). If matter N needs to be described by m characters of $c_1, c_2, \dots, c_m$ and the corresponding quantity values of $x_1, x_2, \dots, x_m$, then it can be called as the m -dimension ME, which is expressed by:

$$R = (N, c, x) = \begin{bmatrix} N & c_1 & x_1 \\ & c_2 & x_2 \\ & \mathbf{M} & \mathbf{M} \\ & c_m & x_m \end{bmatrix} \quad (1)$$

The detailed steps of ME analysis involve:

- Establishment of the classical domain

$$R_{Bk} = (N_{Bk}, c, x_{Bk}) = \begin{bmatrix} N_{Bk} & c_1 & x_{Bk1} \\ & c_2 & x_{Bk2} \\ & \mathbf{M} & \mathbf{M} \\ & c_m & x_{Bkm} \end{bmatrix} = \begin{bmatrix} N_{Bk} & c_1 & [a_{Bk1}, b_{Bk1}] \\ & c_2 & [a_{Bk2}, b_{Bk2}] \\ & \mathbf{M} & \mathbf{M} \\ & c_m & [a_{Bkm}, b_{Bkm}] \end{bmatrix} \quad (2)$$

In this matrix, N_{Bk} is the k^{th} -grade ($k=1, 2, \dots, g$) standard object, $x_{Bkj} = [a_{Bkj}, b_{Bkj}]$ presents the interval quantity value of N_{Bk} with respect to c_j ($j=1, 2, \dots, m$), and classical domain depicts the corresponding attributes of each rank.

- Determination of the joint domain

Through Equation (2), the joint domain object ME matrix can be obtained:

$$R_p = (N_p, c, x_p) = \begin{bmatrix} N_p & c_1 & [a_{p1}, b_{p1}] \\ & c_2 & [a_{p2}, b_{p2}] \\ & \mathbf{M} & \mathbf{M} \\ & c_m & [a_{pm}, b_{pm}] \end{bmatrix} \quad (3)$$

where N_p is the collectivity of event grades, $x_{pj} = [a_{pj}, b_{pj}]$ stands for the interval value of N_p in regard to c_j and obviously, $x_{Bkj} \subset x_{pj}$.

- Construction of the expected assessment ME

The ME to be appraised could be denoted by:

$$R_i = (N_i, c, x_i) = \begin{bmatrix} N_i & c_1 & x_{i1} \\ & c_2 & x_{i2} \\ & \mathbf{M} & \mathbf{M} \\ & c_m & x_{im} \end{bmatrix} \quad (4)$$

It should be noted that the matter to be evaluated is N_i ($i=1, 2, \dots, n$), while x_i is the

real dataset of each character c_j .

Additionally, we define the extension sets (interval numbers) as $[\bar{A}] = [a_1, b_1]$ and $[\bar{B}] = [a_2, b_2]$, then the basic operations or rules on interval numbers are stated as follows:

1. $[a_1, b_1] \pm [a_2, b_2] = [a_1 \pm a_2, b_1 \pm b_2]$;
2. $[a_1, b_1] \cdot [a_2, b_2] = [a_1 \cdot a_2, b_1 \cdot b_2]$, $[a_1, b_1] / [a_2, b_2] = [a_1 / a_2, b_1 / b_2]$;
($a_2 \neq 0, b_2 \neq 0$)
3. if $\lambda \geq 0$, then $\lambda[a_1, b_1] = [\lambda a_1, \lambda b_1]$; if $\lambda < 0$, then $\lambda[a_1, b_1] = [\lambda b_1, \lambda a_1]$.

2.2 Comprehensive Weighting Method

For the sake of handling the contradictions among multiple objectives, weights should be brought in to measure the significance of each indicator. The quantification of weights reveals the importance degree, heterogeneity and reliability of the index attribute values by decision makers, which is the core issue in the procedure of scheme optimization and decision support. With the overall consideration of factors' subjectivity and objectivity, an integrated weighting model based on consistent matrix analysis (CMA) and information entropy (IE) approaches is created in this work to determine the weight vector, ensuring the scientificity, rationality and practicability. Effectiveness and applicability of this method will be verified by a didactical case hereinafter.

2.2.1 CMA technique

AHP, a flexible and widely-used multi-criteria decision-making method, was first proposed by

Saaty in the 1980s. Whereas traditional AHP often required the consistency check and repeated establishments of the decision matrix caused much more workloads (Sharma et al. 2008). CMA technique is introduced with the purpose of avoiding extra efforts, and followings are the computation steps of CMA.

- Create the decision matrix

$$A = \{a_{ij}\}_{m \times m} \quad (5)$$

where $a_{ij} = 1$ ($i = j$), $a_{ij} = 1 / a_{ji}$.

9-Scale linguistic variables are adopted to compare the relative importance between any two dimensions. Table 1 illustrates the linguistic variables to interpret the essentiality comparison. In view of the pairwise comparison, decision matrix A is $A = \{a_{ij}\}_{m \times m}$, where a_{ij} is the scale of a_i comparing with a_j , while the scale is $1 / a_{ij}$ when a_j comparing with a_i .

- Order

$$b_{ij} = \sqrt[m]{\prod_{h=1}^m a_{ih} \cdot a_{hj}}, \quad h = 1, 2, \dots, m \quad (6)$$

and the consistent matrix is:

$$B = \{b_{ij}\}_{m \times m} \quad (7)$$

where $b_{ij} = 1$ ($i = j$), $b_{ij} = 1 / b_{ji}$, $b_{ij} = b_{ih} \cdot b_{hj}$.

- Calculate the weights of indicators w_j^{CMA}

$$c_j = \sqrt[m]{\prod_{h=1}^m b_{jh}}, \quad j = 1, 2, \dots, m, \quad h = 1, 2, \dots, m \quad (8)$$

$$w_j^{CMA} = \frac{c_j}{\sum_{h=1}^m c_h} \quad (9)$$

As mentioned before, CMA method can not only reduce the work resulted from the repeated establishment of the decision matrix, but guarantee the consistency of the decision matrix. Thus the course of ascertaining weights will be simplified and can be regarded as a

subjective weighting method.

Table 1. Scale of relative importance used in the pairwise comparison.

2.2.2 IE approach

The entropy concept firstly appeared in thermodynamics, and was carried into information theory later by Shannon, the contribution of factors was reflected by the degree of data disorder, which could be analyzed by IE approach (Zhang et al. 2008). It can measure the amount of useful information with the dataset provided. So in this investigation, the IE method is applied to acquire the objective weights of assessment indicators.

- Determine the initial matrix

Data pre-processing can transform the original sequence into a comparable sequence.

For this purpose, the values of appraisal indexes should be normalized in the range of 0–1 (Çaydaş et al. 2008).

For benefit index:

$$t_{ij} = \frac{x_{ij} - \min_j \{x_{ij}\}}{\max_j \{x_{ij}\} - \min_j \{x_{ij}\}} \quad (10)$$

For cost index:

$$t_{ij} = \frac{\max_j \{x_{ij}\} - x_{ij}}{\max_j \{x_{ij}\} - \min_j \{x_{ij}\}} \quad (11)$$

where x_{ij} is the factor value of alternative schemes set, t_{ij} is the dimensionless value, and the integrated initial matrix can be gained as $T = (t_{ij})_{n \times m}$.

- Define the IE

$$H_i = -k \sum_{j=1}^m f_{ij} \ln f_{ij}, \quad i = 1, 2, \dots, n \quad (12)$$

where $f_{ij} = t_{ij} / \sum_{j=1}^m t_{ij}$, $k = 1/\ln m$, and suppose when $t_{ij} = 0$, $f_{ij} = 0$.

- Compute the weight vector w_j^{IE}

$$w_j^{IE} = \frac{1 - H_i}{n - \sum_{i=1}^n H_i} \quad (13)$$

2.2.3 Combination weights

Adopting the addition and multiplication methods (Chen et al. 2007), the combinational weight of assessment index can be denoted as below:

$$w_j^C = \frac{w_j^{CMA} \cdot w_j^{IE}}{\sum_{j=1}^m w_j^{CMA} \cdot w_j^{IE}}, \quad j = 1, 2, \dots, m \quad (14)$$

On the one hand, the combined weight vector can indicate the subjective decision and intuition of decision makers; on the other hand, this technique measures the amount of useful information with the primary data provided, which can simultaneously guarantee the evaluation results are more efficacious and convincing.

2.3 Mathematical Model Development

Define $G(1, 2, \dots, g)$ as the estimation scale and F stands for the appraisal set. It is

supposed that there are five grades, then we get a typical assessment set F , namely: $F = \{ \text{Grade A (Excellent), Grade B (Good), Grade C (Medium), Grade D (General), Grade E (Poor)} \}$. As Equations (15–18) demonstrate, the ownership among indicator's classical domain, joint domain and evaluation value can be conveyed through the correlation function $k_G(x_j)$, to which the bigger, the better.

$$k_G(x_j) = \begin{cases} \frac{\rho(x_j, x_{Gj})}{\left[\rho(x_j, x_{pj}) - \rho(x_j, x_{Gj}) \right]} & x_j \notin x_{Gj} \\ \frac{-\rho(x_j, x_{Gj})}{|x_{Gj}|} & x_j \in x_{Gj} \end{cases} \quad (15)$$

$$\rho(x_j, x_{Gj}) = \left| x_j - (a_{Gj} + b_{Gj}) / 2 \right| - (b_{Gj} - a_{Gj}) / 2 \quad (16)$$

$$\rho(x_j, x_{pj}) = \left| x_j - (a_{pj} + b_{pj}) / 2 \right| - (b_{pj} - a_{pj}) / 2 \quad (17)$$

$$|x_{Gj}| = |a_{Gj} - b_{Gj}| \quad (18)$$

where $x_{Gj} = [a_{Gj}, b_{Gj}]$ and $x_{pj} = [a_{pj}, b_{pj}]$ are the interval ranges of the classical domain and joint domain, respectively.

According to the ME analysis theory and comprehensive (both subjective and objective) weighting method, a data-oriented multi-criteria matter-element decision-making (MCMEDM) model is established in this paper eventually where both the correlation degrees and rank division values are considered, as shown below.

$$\max_{1 \leq i \leq n} G_i^* = \max_{1 \leq i \leq n} \left\{ \frac{\sum_{k=1}^g g \cdot \bar{k}_G(N_i)}{\sum_{k=1}^g \bar{k}_G(N_i)} \right\} \quad (19a)$$

$$\bar{k}_G(N_i) = \frac{k_G(N_i) - \min k_G(N_i)}{\max k_G(N_i) - \min k_G(N_i)} \quad (19b)$$

$$k_G(N_i) = \sum_{j=1}^m w_j^C \cdot k_G(x_j) \quad (19c)$$

$$s.t. : \sum_{j=1}^m w_j^C = 1 \quad (19d)$$

In this flexible MCMEDM model, $k_G(N_i)$ expresses the integrative relation degree, while G_i^* manifests the eigenvalues of the grade variables, of which the greater, the better.

The proposed model logically and effectively solves the problem of nonlinearity and incompatibility among different targets in LRT planning. Moreover, it will help better tackle the contradictions in engineering reality as a new mathematical tool. Due to the favorable scalability and portability, this methodology can be used to optimize LRT system networks, which would be extended and popularized to other related or similar fields.

3. Multi-Level Assessment Index System

A scientific rail transit network planning can not only provide reasonable suggestions or reference for government departments, but also effectively guide the future development of the city. Since the issues of investment and construction cycle, the particular purposes or objectives of building the LRT system will be deliberated definitely before its actual start.

3.1 Multiple Objectives of LRT Network Planning

After reviewing the relevant literatures, this work finds out that the existing evaluation and optimization of urban rail transit networks focus more on qualitative analysis in American and European cities, which is generally composed of recovering the vitality of downtown areas, promoting the reconstructions of old cities, improving the environment, enhancing the travel

accessibility of residents and realizing the social equity (Gerçek et al. 2004; Ji et al. 2004; Lee 2000; Liu et al. 2011; Wang et al. 2014). By contrast, the concerning about quantitative researches is not thorough enough. The index outline of LRT network planning has been instituted in some Chinese cities on the basis of their particularities, including the structural performance of LRT network, operation condition of passenger transport, implementation of engineering construction, economic and social benefits and urban development strategies (criteria).

LRT network planning has the features of being multi-variable, multi-level and multi-attribute, and the decision factors are numerous and intersected, which is impossible to assess/judge or prioritize only with a single criterion. Taking the principles of systematicness, scientificity and rationality and the above analysis into account, four aspects are consequently discussed and analyzed in this research, which involve the coordination of urban development (I1), properties of network structure (I2), level of operation (I3), and the feasibility of construction project (I4). These four main targets correspond to the government agencies, ministries of urban planning, LRT operation and management, housing and urban-rural development, demonstrating the crucial expectations and concentrations of planners and decision makers on building or developing/approving the urban LRT.

3.2 Selection of Indicators

Multi-criteria assessment index framework (selecting appraisal indexes) is the vital evidence and basis of proving and verifying the LRT planning schemes, which requires the overall

consideration and decision-making analysis from the angle of system coordination. Apparently, the size of factor system will impact the entire workload as well as the reliability of the calculated results. The LRT network is a complicated system that contains diverse and multiple attributes, and it is unrealistic to cover all these indicators. Therefore, the chosen evaluation factors need to comply with the recommended principles:

1. Comprehensiveness and science-based principle — one index usually reflects the state of LRT network project from one side and has some limitations (cannot convey the complete performance). Nevertheless, the multi-criteria assessment factor outline should make an effort to entirely illustrate the idiographic and inherent descriptions of the object to be evaluated;
2. Representation principle — the chosen indicators should be the major and representative indexes of the LRT network;
3. Feasibility and reasonability principle — an explicit appraisal concept, acquirable data and preferable maneuverability are required in the decision-making system;
4. Comparability principle — commensurabilities of influential factors are necessary for quick comparison of the different indexes;
5. Sufficiency principle — the status of LRT networks need to be fully reflected in various aspects.

Combining the multi-objective and suggested fundamentals of appraising LRT network with the real-case study in Jining, a multi-criteria decision-making factor system is founded concretely as Figure 1 expounds. The indicator sets are then established for the alternative optimization and decision-making support of LRT network projects, whose bottom hierarchy

is formed by eleven sub-indicators (*I11–I42*, in Fig. 1). These eight quantitative factors and three qualitative indexes are explained for details in the succeeding section.

Fig. 1. Frame structure of multi-criteria evaluation indicators.

In Fig. 1, *I11* represents the coordination between LRT networks and urban spatial development (qualitatively); *I12* is the LRT lines passing by the three municipal public service centers in Jining; *I13* is the number of external traffic hubs connecting with the LRT network. *I21* is the percent of LRT network coverage in the planning area of Jining, characterizing the overall structural performance of this network (%); *I22* is the transfer coefficient, shown as the ratio of passenger ridership to resident trips and it measures the connectivity within the LRT network (dimensionless); *I23* is the residents' average vehicle travel time (minutes). *I31* is the load intensity of LRT lines, presenting the ratio between the average daily passenger person-kilometers and operation length of the LRT lines (ten thousand passenger kilometers per day/kilometers); *I32* is the section non-equilibrium factor of passenger flow, expressed as the ratio of maximum section passenger flow to average passenger flow of other sections at the same time (dimensionless); *I33* reflects the flexibility of operation and organization (qualitatively). *I41* is the number of crossing rivers, railways and turns due to route laying; *I42* is the rationality of phased construction program (qualitatively).

Only *I22*, *I23*, *I32* and *I41* are cost indexes in all these eleven factors, while the rest are benefit indicators.

4. Empirical Analysis

On account of the ME analysis (extenics) theory, each of the three projects could be regarded as one ME. For the specific case of Jining, a data-driven MCMEDM support model constructed via Equation (19) is utilized to evaluate, analyze and optimize the LRT network alternatives. Moreover, the availability, reliability and practicability of the suggested model are investigated and validated in this work. Figure 2 presents the implementation of performance evaluation and alternative prioritization integrally.

Fig. 2. Configuration diagram of steps to be applied in the decision-making process.

4.1 Scheme Context and Basic Data

Jining, a medium-sized city located in eastern China, has already been experiencing the rapid expansion of population and urban scale from an ancient city to a modern one over the last decade. The development of LRT would be effective to alleviate the issues brought by the continuous urbanization and motorization in a scientific way, for example, land use, spatial management, traffic congestion and environmental pollution. Besides, the construction of LRT system was becoming really imperative and necessary, hence, we designed and planned the three options (selection set) for decision-making.

A numerical value should be given to each sub-factor in the assessment and optimization frame. For quantitative indexes, values could be acquired from different designing outcomes, such as $I12$, $I13$ and $I41$. Additionally, quantitative values of $I21$, $I22$, $I23$, $I31$ and $I32$ could be obtained through the TransCAD (a transportation planning software). As for each qualitative indicator ($I11$, $I33$ and $I42$), a score ranged in $[0, 5]$ was given by the decision group owing to the members' knowledge and expertise (Gerçek et al. 2004; Liu et al. 2011), where 5 was the highest value and 0 was the minimum value. Subsequently, Table 2 describes the collection of initial data of these three plans. And the information of the three tracks is well illustrated in Fig. 3b, including the origin and destination, railway station, distribution center, LRT station, etc. With this figure and overall computed results, the following discussion would become more rigorous, convincing and clear, which could better reflect the logic and integrity of this article.

Table 2. Dataset of Jining light rail transit networks.

4.2 Model Application and Calculation Processing

In the light of the multiple targets index system and combination weight vector reckoned by the CMA/IE methodology, the proposed model is used to compute the integrated evaluation values of the foresaid three alternatives. And then proceeding to the next step, the LRT network planning schemes of Jining are assessed and optimized for decision-making, which the

calculating procedures are organized as follows.

4.2.1 Standard normalization and the computation of compositive weight

First of all, the original data of these three projects should be normalized using Equations (10–11), and the incipient decision matrix is gained as Table 3 manifests. Secondly, subjective weights are calculated by consistency matrix analysis method according to Table 1 and Equations (5–9). Table 4 enumerates the pairwise comparison matrix of the top hierarchy indicators. As there is not abundant space to list the numeration course of indexes in other hierarchies, the final calculation outcomes are shown in Table 3 by the same token. Thirdly, objective weights are obtained in terms of Equations (12–13), also revealed in Table 3 minutely. At length, the last column of Table 3 represents synthetical factor weight values on the strength of Equation (14).

Table 3. Normalized results and the computation process of integrated weights.

Table 4. Pairwise comparison matrix and weights of the first hierarchy factors.

4.2.2 Confirming the fuzzy appraisal set and degree of membership

In view of the actual situation of Jining case and specialties of the LRT network alternatives, the standard and scope of the assessment index framework (Fig. 1) can be confirmed in this paper. And the fuzzy evaluation set consists of five linguistic variables (that is, Excellent, Good, Medium, General and Poor) for sake of recognizing the optimal planning, where each variable will be regarded as a judgment criterion of the second-layer sub-indicators with the corresponding grades (e.g., A, B, C, D or E). In addition, Table 5 explains and recommends the fuzzy evaluation intervals of the membership function of every basic index, offering the foundation of subsequent discussion and analyses.

Table 5. Fuzzy membership function of assessment indicator system.

Pondering the above explanation, joint and classical domains of the extension ME to be assessed will be determined (vide infra). Given the limited length of this article, the following examples are provided, while other calculations are equally available.

- Classical domain ME matrix:

$$R_{BA} = (N_{BA}, c, x_{BA}) = \begin{bmatrix} N_{BA} & c_1 & [4.0, 5.0] \\ & c_2 & [8, 10] \\ & c_3 & [18, 22] \\ & c_4 & [0.45, 0.50] \\ & c_5 & [1.2, 1.1] \\ & c_6 & [17, 16] \\ & c_7 & [0.9, 1.0] \\ & c_8 & [1.3, 1.2] \\ & c_9 & [4.0, 5.0] \\ & c_{10} & [12, 10] \\ & c_{11} & [4.0, 5.0] \end{bmatrix} \quad \text{L} \quad R_{BC} = (N_{BC}, c, x_{BC}) = \begin{bmatrix} N_{BC} & c_1 & [2.0, 3.0] \\ & c_2 & [4, 6] \\ & c_3 & [10, 14] \\ & c_4 & [0.35, 0.40] \\ & c_5 & [1.4, 1.3] \\ & c_6 & [19, 18] \\ & c_7 & [0.7, 0.8] \\ & c_8 & [1.5, 1.4] \\ & c_9 & [2.0, 3.0] \\ & c_{10} & [16, 14] \\ & c_{11} & [2.0, 3.0] \end{bmatrix} \quad \text{L} \quad (20)$$

- Joint domain ME matrix:

$$R_p = (N_p, c, x_p) = \begin{bmatrix} N_p & c_1 & [0.0, 5.0] \\ & c_2 & [0, 10] \\ & c_3 & [2, 22] \\ & c_4 & [0.25, 0.50] \\ & c_5 & [1.6, 1.1] \\ & c_6 & [22, 16] \\ & c_7 & [0.5, 1.0] \\ & c_8 & [1.7, 1.2] \\ & c_9 & [0.0, 5.0] \\ & c_{10} & [20, 10] \\ & c_{11} & [0.0, 5.0] \end{bmatrix} \quad (21)$$

These interpretations offer a theoretical basis for the overall operation and optimization, as well as the example verification of reckoning synthetic evaluation values.

4.3 Overall Results and Discussion

Based on Equations (15–18, 20–21) and Table 5, correlation degrees are interpreted clearly and aggregately in Table 6. Afterwards, the multi-objective comprehensive correlation degrees will

be reckoned in accordance with Equations (19c–19d) and Table 3 (combined weights) as stated at the rightmost column of Table 6. This table shows the specific computation results of correlation degrees (sub-item data) about the Designs #1 – #3.

Table 6. Calculation results of the correlation degrees of Projects #1 to #3.

Further, the eigenvalues of rank variables are acquired in light of the MCMEDM model created by Equations (19a–19b) and grade division values (5, 4, 3, 2, 1 standing for the evaluation order of A, B, C, D and E). Finally, we can get $G_{\#1}^* = 3.67406$, $G_{\#2}^* = 3.46307$, $G_{\#3}^* = 3.69047$, scilicet $G_{\#2}^* < G_{\#1}^* < G_{\#3}^*$ in this case. Thus, the optimum alternative is Project #3 and the worse one is #2. Nevertheless, the score of Scheme #1 is just slightly lower than #3 (**-0.1601** and **-0.0732** VS **-0.1293** and **-0.1144**), which can be deemed as a suboptimal project. In virtue of the three integrated assessment values, the discussion and exploration are mainly focused on Projects #3 and #1 ultimately.

Fig. 3a. Graphical illustration of the correlation degree function about each ranking sub-factor.

Fig. 3b. Schematic diagram of Jining light rail transit network planning schemes.

From the horizontal and longitudinal comparisons among the datasets (deepened correlation degrees) in Table 6, and along with the variation/changing trend of correlation degree functions mapped in Fig. 3a, it can be seen that Scheme #3 is better than #1 in the coordination of urban development ($I11$, $I12$, $I13$), as well as the properties of network structure ($I21$, $I22$, $I23$). While regarding the level of operation ($I31$, $I32$, $I33$) and the feasibility of construction projects ($I41$, $I42$), Design #1 is relatively superior to #3. What is more, managers or decision makers tend to unify the merits or advantages of Plans #3 and #1 respectively (Fig. 3b) when ascertaining the best possible solution in engineering practice. Alternatively, during the final measurement and argumentation, the optimal design may be amended and conformed somewhat by decision experts (regulatory agencies). In the later stage, a cumulative superiority would be generated to support/affect the multi-criteria decision-making course of alternative LRT networks, an analogy to the Matthew Effect, which could reflect the applicability, flexibility and polytrope of this performance assessment and alternatives prioritization model.

5. Conclusions

The quest for meliorating the assessment of LRT networks has afforded the opportunity to develop effective methodology and powerful tools for decision-making and optimization. This paper comes to the following conclusions and summary on account of the rigorous calculation procedures, case analysis and discussion.

- As the creation of multi-index evaluation system, multiple goals of building urban

LRT, the expectations and metrics of different departments are discussed. Eleven factors of the coordination of urban development (I1), attributes of network structure (I2), operation level (I3) and the feasibility of engineering project (I4) are conducted for the subsequent prioritization and determination.

- CMA and IE methods are applied to reckon the integrated weights of each appraisal indicators instead of just the single-method, pondering both subjectivity and objectivity and improving the outcome precision concurrently. A case study in Jining is implemented to examine and verify the established mathematical model — MCMEDM model, employing the raw datasets.

- The quantification results show that this data-oriented approach is scientific, logical, clear and direct, which can provide decision and policy makers with a reasonable and effective basis, as well as the theoretical and data support. Moreover, the ideal plan gained via the proposed model may be adjusted and integrated by government regulators or decision-makers in the final argument when coming to/before the real construction of specific LRT network projects. This flexible modeling process would be the reference and foundation of performance evaluation and alternative optimization for the LRT network planning in other cities, and be spread to other related/similar fields.

In future research, there are three key directions in which the work presented in this study might be extended. Some complex decision variables could be considered and the performance evaluation and alternative optimization model needs to be changed accordingly. This modified model will be used to solve the problems in large-scale systems, and therefore improve the calculation ability and efficiency markedly.

Notation

A	decision matrix	$k_G(N_i)$	integrative relation degree
$\overline{A}, \overline{B}$	extension sets	$k_G(x_j)$	correlation function
a_1, a_2	lower limit of interval numbers	m	number of characters
a_{ij}	scale of relative importance	N	matter-element (ME)
B	consistent matrix	N_{Bk}	classical domain ME
b_1, b_2	upper limit of interval numbers	N_p	joint domain ME
b_{ij}	order	N_i	ME to be evaluated
c	character	R, R_{Bk}, R_p, R_i	ternary group
F	a typical assessment set	T	integrated initial matrix
G	estimation scale	t_{ij}	dimensionless value
G_i^*	eigenvalues	w_j	weights of indicators
g	rank division values	x	corresponding quantity values/interval ranges
H_i	information entropy	λ	coefficient
k	grade	ρ	correlation degrees

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this article.

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Tables

Table 1. Scale of relative importance used in the pairwise comparison.

Scale of relative importance	Linguistic variable	Comparative judgment
1	Equally important	a_i and a_j are equally important
3	Weakly important	a_i is weakly more important than a_j
5	Essentially important	a_i is essentially more important than a_j
7	Very strongly important	a_i is very strongly more important than a_j
9	Absolutely important	a_i is absolutely more important than a_j
2, 4, 6, 8 is an intermediate scale		

Table 2. Dataset of Jining light rail transit networks.

Assessment index	Indicator value		
	Project #1	Project #2	Project #3
<i>I11 (qualitatively)</i>	4.35	4.65	4.65
<i>I12</i>	3	6	8
<i>I13</i>	12	12	14
<i>I21 (%)</i>	36	38	40
<i>I22 (dimensionless)</i>	1.16	1.18	1.25
<i>I23 (minutes)</i>	18.78	19.36	18.25
<i>I31 (ten thousand passenger kilometers)</i>	0.95	0.88	0.93

per day/kilometers)

<i>I32 (dimensionless)</i>	1.42	1.51	1.51
<i>I33 (qualitatively)</i>	3.50	3.00	3.00
<i>I41</i>	14	15	15
<i>I42 (qualitatively)</i>	4.50	4.50	3.50

Note: The meaning and acquisition or calculation formulas of *I11–I42* are introduced in detail in Sections 3.2 and 4.1.

Table 3. Normalized results and the computation process of integrated weights.

Sub-factor	Normalization of three alternatives			w_j^{CMA}	w_j^{IE}	w_j^C
<i>I11</i>	0.000	1.000	1.000	$0.36469 \times 0.49339 = 0.17993$	0.05485	0.11685
<i>I12</i>	0.000	0.600	1.000	$0.36469 \times 0.19580 = 0.07141$	0.05912	0.04998
<i>I13</i>	0.000	0.000	1.000	$0.36469 \times 0.31081 = 0.11335$	0.14861	0.19944
<i>I21</i>	0.000	0.500	1.000	$0.27710 \times 0.30351 = 0.08410$	0.06251	0.06224
<i>I22</i>	1.000	0.778	0.000	$0.27710 \times 0.17749 = 0.04918$	0.05590	0.03255
<i>I23</i>	0.523	0.000	1.000	$0.27710 \times 0.51900 = 0.14382$	0.06159	0.10488
<i>I31</i>	1.000	0.000	0.714	$0.23301 \times 0.50000 = 0.11651$	0.05674	0.07827
<i>I32</i>	1.000	0.000	0.000	$0.23301 \times 0.25000 = 0.05825$	0.14861	0.10250
<i>I33</i>	1.000	0.000	0.000	$0.23301 \times 0.25000 = 0.05825$	0.14861	0.10250
<i>I41</i>	1.000	0.000	0.000	$0.12520 \times 0.50000 = 0.06260$	0.14861	0.11014
<i>I42</i>	1.000	1.000	0.000	$0.12520 \times 0.50000 = 0.06260$	0.05485	0.04065

Table 4. Pairwise comparison matrix and weights of the first hierarchy factors.

Top layer	Decision matrix				Consistent matrix				c_j	Weight
	<i>CUD</i>	<i>PNS</i>	<i>LO</i>	<i>FCP</i>	<i>CUD</i>	<i>PNS</i>	<i>LO</i>	<i>FCP</i>		
<i>CUD</i>	1.000	1.000	2.000	3.000	1.000	1.316	1.565	2.913	1.56508	0.36469
<i>PNS</i>	1.000	1.000	1.000	2.000	0.760	1.000	1.189	2.213	1.18921	0.27710
<i>LO</i>	0.500	1.000	1.000	2.000	0.639	0.841	1.000	1.861	1.00000	0.23301
<i>FCP</i>	0.333	0.500	0.500	1.000	0.343	0.452	0.537	1.000	0.53728	0.12520

Abbreviations: CUD – coordination of urban development; PNS – properties of network structure; LO – level of operation; FCP – feasibility of construction project.

Table 5. Fuzzy membership function of assessment indicator system.

Bottom layer index	Fuzzy sets of evaluation factors				
	A (Excellent)	B (Good)	C (Moderate)	D (General)	E (Poor)
<i>I11</i>	[4.0, 5.0)	[3.0, 4.0)	[2.0, 3.0)	[1.0, 2.0)	[0.0, 1.0)
<i>I12</i>	[8, 10)	[6, 8)	[4, 6)	[2, 4)	[0, 2)
<i>I13</i>	[18, 22)	[14, 18)	[10, 14)	[6, 10)	[2, 6)
<i>I21</i>	[0.45, 0.50)	[0.40, 0.45)	[0.35, 0.40)	[0.30, 0.35)	[0.25, 0.30)
<i>I22</i>	[1.1, 1.2)	[1.2, 1.3)	[1.3, 1.4)	[1.4, 1.5)	[1.5, 1.6)
<i>I23</i>	[16, 17)	[17, 18)	[18, 19)	[19, 20)	[20, 22)
<i>I31</i>	[0.9, 1.0)	[0.8, 0.9)	[0.7, 0.8)	[0.6, 0.7)	[0.5, 0.6)

<i>I32</i>	[1.2, 1.3)	[1.3, 1.4)	[1.4, 1.5)	[1.5, 1.6)	[1.6, 1.7)
<i>I33</i>	[4.0, 5.0)	[3.0, 4.0)	[2.0, 3.0)	[1.0, 2.0)	[0.0, 1.0)
<i>I41</i>	[10, 12)	[12, 14)	[14, 16)	[16, 18)	[18, 20)
<i>I42</i>	[4.0, 5.0)	[3.0, 4.0)	[2.0, 3.0)	[1.0, 2.0)	[0.0, 1.0)

Table 6. Calculation results of the correlation degrees of Projects #1 to #3.

Index													
Grade		<i>I11</i>	<i>I12</i>	<i>I13</i>	<i>I21</i>	<i>I22</i>	<i>I23</i>	<i>I31</i>	<i>I32</i>	<i>I33</i>	<i>I41</i>	<i>I42</i>	$k_G(N_i)$ ^a
A	#1	0.3500	-0.6250	-0.3750	-0.4500	0.4000	-0.3904	0.5000	-0.3529	-0.2500	-0.3333	0.5000	-0.1601
	#2	0.3500	-0.3333	-0.3750	-0.3684	0.2000	-0.4720	-0.1429	-0.5250	-0.3333	-0.3750	0.5000	-0.2366
	#3	0.3500	0.0000	-0.3333	-0.3333	-0.2500	-0.3571	0.3000	-0.5250	-0.3333	-0.3750	-0.2500	-0.2079
	#1	-0.3500	-0.5000	-0.1667	-0.2667	-0.4000	-0.2191	-0.5000	-0.0833	0.5000	0.0000	-0.5000	-0.1685
B	#2	-0.6500	0.0000	-0.1667	-0.1429	-0.2000	-0.3400	0.2000	-0.3667	0.0000	-0.1667	-0.5000	-0.2209
	#3	-0.6500	0.0000	0.0000	0.0000	0.5000	-0.1000	-0.3000	-0.3667	0.0000	-0.1667	0.5000	-0.1293
	#1	-0.6750	-0.2500	0.5000	0.2000	-0.7000	0.2200	-0.7500	0.2000	-0.2500	0.0000	-0.7500	-0.0732
	#2	-0.8250	0.0000	0.5000	0.4000	-0.6000	-0.1200	-0.4000	-0.0500	0.0000	0.5000	-0.7500	-0.0157
C	#3	-0.8250	-0.5000	0.0000	0.0000	-0.2500	0.2500	-0.6500	-0.0500	0.0000	0.5000	-0.2500	-0.1144
	#1	-0.7833	0.5000	-0.1667	-0.0833	-0.8000	-0.0733	-0.8333	-0.2667	-0.5000	-0.3333	-0.8333	-0.3531
	#2	-0.8833	-0.3333	-0.1667	-0.2000	-0.7333	0.3600	-0.6000	0.1000	-0.3333	-0.1667	-0.8333	-0.2748
	#3	-0.8833	-0.6667	-0.3333	-0.3333	-0.5000	-0.2500	-0.7667	0.1000	-0.3333	-0.1667	-0.5000	-0.3889
E	#1	-0.8375	-0.2500	-0.3750	-0.3529	-0.8500	-0.3050	-0.8750	-0.4500	-0.6250	-0.5000	-0.8750	-0.5361

#2	-0.9125	-0.5000	-0.3750	-0.4000	-0.8000	-0.1951	-0.7000	-0.3214	-0.5000	-0.3750	-0.8750	-0.4937
#3	-0.9125	-0.7500	-0.5000	-0.5000	-0.6250	-0.4375	-0.8250	-0.3214	-0.5000	-0.3750	-0.6250	-0.5567

Note: ^a Multi-attribute comprehensive correlation degree.

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Figure Legends

Fig. 1. Frame structure of multi-criteria evaluation indicators.

Fig. 2. Configuration diagram of steps to be applied in the decision-making process.

Fig. 3a. Graphical illustration of the correlation degree function about each ranking sub-factor.

Fig. 3b. Schematic diagram of Jining light rail transit network planning schemes.

Fig. 1. Frame structure of multi-criteria evaluation indicators.

182x52mm (600 x 600 DPI)

Fig. 2. Configuration diagram of steps to be applied in the decision-making process.

318x299mm (300 x 300 DPI)

Plan #1

Plan #2

Plan #3