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Article

Transfer Scheme Evaluation Model for a Transportation Hub based on Vectorial Angle Cosine

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Abstract: As the most important node in public transport network, efficiency of a transport hub determines the entire efficiency of the whole transport network. In order to put forward effective transfer schemes, a comprehensive evaluation index system of urban transport hubs' transfer efficiency was built, evaluation indexes were quantified, and an evaluation model of a multi-objective decision hub transfer scheme was established based on vectorial angle cosine. Qualitative and quantitative analysis on factors affecting transfer efficiency is conducted, which discusses the passenger satisfaction, transfer coordination, transfer efficiency, smoothness, economy, *etc*. Thus, a new solution to transfer scheme utilization was proposed.

Keywords: vectorial angle cosine; transfer scheme; evaluation index system; quantitative indicators; evaluation model

1. Introduction

In recent years, along with the accelerated urbanization and motorization, travel demand of passengers has increased greatly. An urban public transport hub is the key node among the whole transit network. An efficient transfer articulation system and rational planning of passenger flow line play a vital role in improving the overall efficiency of a transport hub. In our country, the design of a hub transfer program is still in an immature stage. However, some large cities have plans to build a number of passenger transportation hubs. After their completion, the transfer passenger flow of some of them is great. However, this is due to passenger transport demand being excessive in our cities. This causes many issues, including the fact that a badlz designed hub cannot be concealed. How to evaluate and optimize the transfer scheme has become an interesting research topic.

Current approaches for hub transfer scheme evaluation involves: fuzzy multi-attribute decision making method [1], generalized utility function [2], the gray system theory [3], *etc*. Although the transfer efficiency can be evaluated by these methods, due to computational complexity and limitation of the method itself, using existing methods to evaluate the transfer scheme of transport hub still needs improvement. In recent years, the cosine of the angle between the vector method is widely used in hydrology combination forecasting [4], engineering evaluation [5], interval combination forecasting [6] and other areas. By considering that the evaluation and optimization of hub transfer scheme has similarities with these applications, a multi-objective decision hub transfer scheme evaluation model based on vectorial angle cosine has been established in this paper on the basis of comprehensive consideration on the transfer facility conditions [7–12], economy of transfer hub [13], and transfer characteristics of various modes of transportation [14–19]. A transfer efficiency evaluation indexes system [20–24] was built and qualitative and quantitative analysis of the evaluation indexes were undertaken.

2. Basic Model Based on Vectorial Angle Cosine

The vectorial angle cosine law regards the actual value sequences of the predicted object as a vector; the cosine of the angle between the vector and the predicted values sequences needs to be calculated. In other words, it uses the cosine of the angle as the metrics of prediction accuracy. Assuming completion of a target need to investigate an indicator system which has N indicators, denoted by z_j, $j = 1,\ldots, N$. Now, there are m programs to choose, the indicators vector given by the i-th scheme is $\mathbf{Z}_i = \{z_{ij}\}$, $i = 1,\ldots, m$, $j = 1,\ldots, N$. $\mathbf{Z}_i$ represents the i-th scheme's indicator vector, it comprises N elements. z_{ij} represents the impact factor which is the j-th indicator value that the i-th program has, it is equal to its corresponding indicator value multiply the indicator weight θ_j related to the target, that is $z_{ij} = x_{ij} \cdot \theta_j$, where $\sum_{j=1}^{j=N} \theta_j = 1$, $x_{ij} = \sum_{k=1}^{k=n} x_{ijk} \cdot \omega_k$, $j = 1,\ldots, N$, x_{ij} represents the sequential vector consisted by each indicator value of i-th program, $k = 1,\ldots, n$ represents the sub-indicators corresponded to the index x_{ij}. ω_k represents each sub-index weight related to its corresponding index, $\sum_{k=1}^{k=n} \omega_k = 1$.

Assuming the ideal solution is $\mathbf{Z}^* = (z_1^*, z_2^* \ldots z_j^* \ldots z_N^*)$, $j=1,\ldots, N$, According to the definition of two vector (Set A, B) angular cosine: $\cos\langle A, B\rangle = \frac{AB}{|A| \times |B|}$, cosine formula between the i-th scheme and the best solution can be obtained:

$$\psi_i = \cos < \mathbf{Z}_i \ \ \mathbf{Z}^* >= \frac{\sum_{j=1}^{N} z_{ij} z_j^*}{\sqrt{\sum_{j=1}^{N} z_{ij}^2} \sqrt{\sum_{j=1}^{N} z_j^{*2}}} \quad (1)$$

ψ_i is closer to 1, the corresponding *i*-th scheme's indicator vector $\mathbf{Z}_i = \{z_{ij}\}$ is closer to the ideal solution's $\mathbf{Z}^*$, and the satisfied degree is higher. In particular, when ψ_i=1, the corresponding *i*-th scheme's indicator vector $\mathbf{Z}_i = \{z_{ij}\} = \mathbf{Z}^*$, two schemes completely overlap, the *i*-th scheme is the best solution.

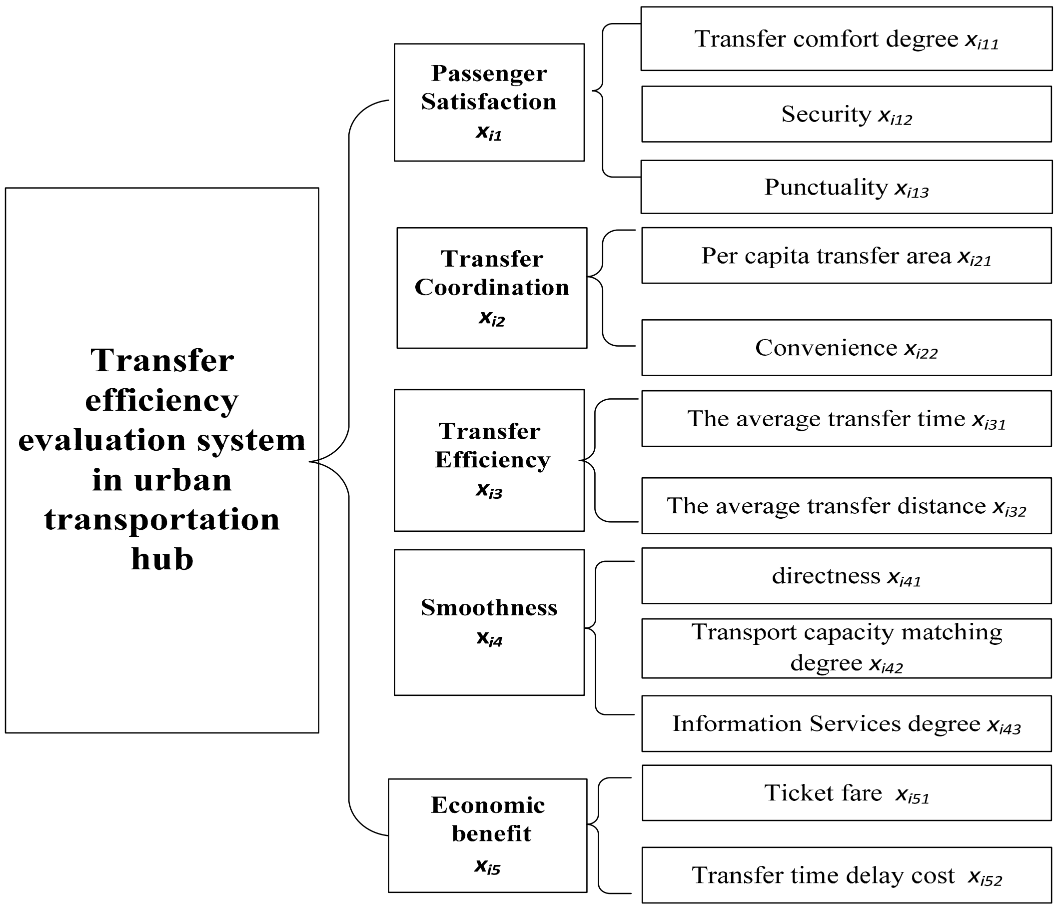
3. Multi-objective Decision Hub Transfer Scheme Evaluation Based on Vectorial Angle Cosine

3.1. Evaluation Index System

The vector cosine law was used to evaluate transfer efficiency in urban transportation hub. The purpose of the paper is to compare the alternative transfer programs according to the overall effectiveness of managers, users and transport providers. A multi-objective fuzzy decision method can be chosen from hub transfer programs. The key concern is how to determine the weight of each index vector.

The relationship among the decision goal, considerate factors and decision objects is established and then they are divided into indicator layer and sub-indicator layer in the target layer, based on the full analysis of the problems exist in transport hub. A passenger transfer efficiency evaluation index system was established as shown in Figure 1.

Figure 1. Passenger transfer efficiency evaluation index system.



3.2. Quantitative Evaluation of Indicators

(1) Transfer comfort degree

Transfer comfort degree reflects the comfort feelings of the passengers in transfer process. It depends on the per capita area of transfer, transfer convenience, the per capita transfer distance and other factors.

$$x_{i11} = \frac{x_{i21} + x_{i22} + x_{i32}}{3} \tag{2}$$

x_{i21} represents per capita transfer area, x_{i22} represents transfer convenience, x_{i32} represents the average transfer distance.

(2) Security

Security is used to measure the safety degree of the passengers in transfer process, it reflects the mutual interference between different traffic flow and rationality degree of facility layout [1]:

$$x_{i12} = L / P \tag{3}$$

where, *P* is the conflict points between the transfer passenger flow lines inside hub facilities. *L* is the average walking distance in transfer hub.

(3) Punctuality

Punctuality is an important indicator to evaluate the merits of traffic modes, it reflects the accuracy degree with which people arrive at the transportation hub, thus ensuring the timely transfer of passengers. There are usually various traffic modes in the transportation hub, such as bus, subway, taxi, bicycle, walking, *etc*. Compared with the bus, the delay probability of other traffic modes is small. So the average delay of bus arrival time is used to represent punctuality:

$$x_{i13} = \frac{\sum_{i=1}^{n} t_{i1} - t_{i0}}{n} \tag{4}$$

where: i represents the *i*-th bus line which connects with the hub, n lines in total, t_{i0} represents the reasonable arriving time of the bus driving on *i*-th bus line, t_{i1} represents actual arrival time of the bus driving on *i*-th bus line.

(4) Per capita transfer area

Per capita transfer facility area is used to measure the transfer facilities' service ability to accommodate passengers; it reflects the congestion degree and comfort level in the transfer hub, which is calculated as follows:

$$x_{i21} = S / Q \tag{5}$$

where: Q is the total number of transfer passengers in traffic hub, S is the total transfer area of the hub.

(5) Convenience

Convenience is used to measure the easy degree of the passengers' transfer. It is the function of the average transfer distance, transfer lines slope and a variety of other transfer factors. It can be calculated as follows:

$$x_{i22} = K_1 A_1 + K_2 A_2 \tag{6}$$

where: $A_1 = \frac{\sum_{i=1}^{N} n_i \times d_i}{\sum_{i=1}^{N} n_i}$, $A_2 = \cos\theta = \frac{L_1}{L_2}$, A_1 represents the average transfer distance to other transit line. i represents other transit line, N is the total amount of all transit lines. n_i represents the number of passenger who transfer to the i-th transit line, d_i represents the transfer distance to the i-th transit line; A_2 represents transfer line slope, using transfer stairs angular cosine to represent, L_1 represents horizontal distance of the stair, L_2 represents the tilt length of the stair. K_1, K_2 are the coefficients.

(6) Average transfer time

Transfer time is the time passengers spend on completing the transfer between one traffic mode and other traffic modes. Take rail traffic for example, the calculation formula is as follows:

$$x_{i31} = \sum Q_i T_i / \sum Q_i \; ; \; T_i = T_c + T_{i1} + T_{i2}, \; i = 1,2,3 \tag{7}$$

where: Q_i is the exchange passenger flow between rail traffic and the i-th regular traffic (passengers/h); T_i is the walking time transferring to the i-th regular traffic (min); T_c is the retention time passengers get off trains within the transportation hub (min); T_{i1} is walking time from the hub exit to the i-th routine traffic park (min); T_{i2} is the time passengers spend on the i-th routine traffic park (min).

(7) The average transfer distance

Transfer distance means the average walking distance passengers walk to the transfer vehicle during the whole transfer process, the calculation formula is as follows:

$$x_{i32} = \sum Q_i L_j / \sum Q_i \tag{8}$$

where: Q_i is the exchange passenger flow between one traffic mode and the i-th traffic mode (passengers/h), L_j is the walking distance transfer from the traffic mode to the other traffic modes (m).

(8) Directness

Directness shows the degree of transfer difficulty, it is expressed by the proportion between transfer time and total travel time, as shown in formula (9).

$$x_{i41} = \sum_i Q_i T / \sum_i Q_i (t_i + T) \tag{9}$$

where: Q_i is the number of passengers in the i-th transportation district; t_i is the non-transfer time that passengers consumed in the transport process in the i-th transportation district (min); T is the average transfer time within the transport hub (min).

(9) Transport capacity matching degree

Transport capacity matching degree refers to the ability that other transportation modes gather or dismiss passengers, which is calculated by the ratio of passenger quantity transfer from one transit mode to other modes in peak hour and the capacity of other modes.

$$x_{i42} = \frac{Q}{\sum_{i=1}^{n} Q_i'} \quad (10)$$

where: x_{i42} is the matching degree of hub capacity, Q is quantity of passengers need to be dismissed during peak hours, Q_i is the quantity of passengers that choose the *i*-th kind of connected traffic in transportation hub.

(10) Information Services degree

This indicator is the satisfaction level of passengers regarding the information service in urban traffic hubs. It reflects the levels that passengers obtain the transfer information and the various services in the transfer hub.

Information in the transportation hub is divided into outside-station information, guiding information, inside-station information, confirming information, *etc.* It is the guarantee of information services obtained by passengers, and is one of the most important factors to improve travel efficiency and passenger satisfaction rate [21]. It can be expressed by the passengers' satisfaction to the information service (x_{i43}).

(11) Economic benefit

Economic benefit is an important qualitative indicator of the evaluation of transportation hubs, which can be represented by passengers' transfer cost. Transfer cost includes ticket price and transfer time delay cost. Time delay cost can be represented by the product of the transfer time and passenger hourly earnings. So, transfer benefit can be calculated as follows:

$$x_{i5} = x_{i51} + x_{i52} = x_{i51} + E\,t \quad (11)$$

where, x_{i51} is ticket fare, t is transfer time delay, and, x_{i52} is time delay cost. E is passenger hourly earnings.

3.3. Evaluation Index Standardization

Due to different dimensions and magnitude, evaluation indicators need to be standardized before comparison. Quantitative indicators can be divided into cost type (which is negative to efficiency) and contribution type (which is positive to efficiency). Assuming x_{ijk} is the value of the k-th sub-index of the *j*-th indicator of the *i*-th scheme, then its normalized index value is:

Comfort and security indicators: $x_{ijk} = x_{ijk} / x_{ij,\max}$

Other indicators: $x_{ijk} = x_{ij,\min} / x_{ijk}$

$x_{ij,\max}$, $x_{ij,\min}$ respectively represent the maximum and minimum value of the index corresponding to the *j*-th evaluation indicator of the respective scheme.

3.4. Hub Transfer Scheme Evaluation Based on Cosine of the Vector's Angle

AHP method was used to calculate the weights of x_{ijk} relative x_{ij}, thus calculating index vector value corresponding to the *i*-th scheme: $\mathbf{X}_{ij} = \{x_{ij}\} = \{\sum x_{ijk} \cdot \omega_k\}$, $\sum_{k=1}^{k=n} \omega_k = 1$, $i = 1...m, j = 1...N, k = 1...n$. Then, we obtained weight vector $\{\theta_j\}$ of indicator vector $\{x_{ij}\}$ based on the AHP method. $\mathbf{Z}_i = \{z_{ij}\} = \{x_{ij} \cdot \theta_j\}$, $\sum_{j=1}^{j=N} \theta_j = 1$, $j = 1...N$. We calculated the cosine ψ_i of the angle between the index vector $\mathbf{Z}_i = \{z_{ij}\}$ ($i = 1...m$, $j = 1...N$) given by the *i*-th scheme and the ideal solution indicators vector $\mathbf{Z}^*$. The steps of multi-objective decision based on vectorial angle cosine is as follows.

Step 1:

$$x_{ij} = \sum_{k=1}^{k=n} x_{ijk} \cdot \omega_k, \quad \sum_{k=1}^{k=n} \omega_k = 1$$

Step 2:

$$z_{ij} = x_{ij} \cdot \theta_j, \quad \sum_{j=1}^{j=N} \theta_j = 1$$

Step 3:

$$\psi_i = \cos < \mathbf{Z}_i \quad \mathbf{Z}^* >= \frac{\sum_{j=1}^{N} z_{ij} z_j^*}{\sqrt{\sum_{j=1}^{N} z_{ij}^2} \sqrt{\sum_{j=1}^{N} z_j^{*2}}}$$

$$i = 1, \ldots, m; j = 1, \ldots, N$$

According to the results, the larger ψ_i is, the better the *i*-th scheme is. Thus, the scheme corresponding to the maximum ψ_i can be selected, which is the best solution of all evaluation schemes.

4. Application

Let us take the Xidan hub in Beijing as an example. Since a ticket fare of 2 yuan is fixed in Beijing, ticket fare effects can be ignored. In other words, economic benefit can be represented by passenger hourly earnings. That is $x_{i5} = x_{i52} = E_t$. Assume that there are three transfer schemes. Due to various factors, the ideal scheme indicators cannot be fully met. It can only be chosen from the three existing schemes. Sub-index value and weights of the index of all schemes are shown in Table 1:

Table 1. Standardized results of the evaluation indexes.

Evaluation indexes x_{ij}	Evaluation sub-indexes x_{ijk}	Evaluation index values	Ideal scheme	First scheme	Second scheme	Third scheme	ω_k	θ_j
x_{i1}	x_{i11}	Original value	4.8	3.4	3.7	4.5	0.33	0.21
		Normalized value	1.000	0.708	0.771	0.938		
	x_{i12}	Original value	5.0	4.2	4.6	4.8	0.35	
		Normalized value	1.000	0.840	0.920	0.960		
	x_{i13}	Original value	3	5.7	6.2	5.6	0.32	
		Normalized value	1.000	0.526	0.484	0.536		

Table 1. *Cont.*

Evaluation indexes x_{ij}	Evaluation sub-indexes x_{ijk}	Evaluation index values	Ideal scheme	First scheme	Second scheme	Third scheme	ω_k	θ_j
x_{i2}	x_{i21}	Original value	1.5	1.3	1.2	0.9	0.48	0.20
		Normalized value	1.000	0.867	0.800	0.600		
	x_{i22}	Original value	0.895	0.855	0.702	0.825	0.52	
		Normalized value	1.000	0.955	0.784	0.922		
x_{i3}	x_{i31}	Original value	2	9	4	13	0.53	0.22
		Normalized value	1.000	0.222	0.500	0.154		
	x_{i32}	Original value	80	410	220	545	0.47	
		Normalized value	1.000	0.195	0.364	0.147		
x_{i4}	x_{i41}	Original value	0.104	0.098	0.086	0.084	0.30	0.19
		Normalized value	1.000	0.942	0.827	0.808		
	x_{i42}	Original value	0.800	0.854	0.890	0.880	0.38	
		Normalized value	1.000	0.937	0.899	0.909		
	x_{i43}	Original value	0.950	0.880	0.832	0.867	0.32	
		Normalized value	1.000	0.926	0.876	0.913		
x_{i5}	x_{i52}	Original value	2	5	8	6	1.00	0.18
		Normalized value	1.000	0.400	0.250	0.333		
Vector cosine			ψ_0=1	ψ_1	ψ_2	ψ_3		

Take scheme 1 as an example, calculate ψ_1:

Step 1:

$$\mathrm{x}_{ij} = \sum_{k=1}^{k=n} x_{ijk} \cdot \omega_k, \quad \sum_{k=1}^{k=n} \omega_k = 1$$

Available: $$\mathrm{x}_{11} = \sum_{k=1}^{k=n} x_{11k} \cdot \omega_k = x_{111} \cdot \omega_1 + x_{112} \cdot \omega_2 + x_{113} \cdot \omega_3 = 0.69596$$

Similarly available: $\mathrm{x}_{12} = 0.93356$, $\mathrm{x}_{13} = 0.20931$, $\mathrm{x}_{14} = 0.93498$, $\mathrm{x}_{15} = 0.40000$

Step 2:

From the $\mathrm{z}_{ij} = \mathrm{x}_{ij} \cdot \theta_j$, $\sum_{j=1}^{j=N} \theta_j = 1$

Available: $\mathrm{z}_{11} = \mathrm{x}_{11} \cdot \theta_1 = 0.69596 \times 0.21 = 0.1462$,

Similarly available: $z_{12} = 0.1867$, $z_{13} = 0.0460$, $z_{14} = 0.1776$, $z_{15} = 0.0720$, $z_1^* = z_2^* = z_3^* = z_4^* = z_5^* = 1.0000$

Step 3:

$$\psi_1 = \cos < \mathbf{Z}_1 \ \mathbf{Z}^* >= \frac{\sum_{j=1}^{5} z_{1j} z_j^*}{\sqrt{\sum_{j=1}^{5} z_{1j}^2} \sqrt{\sum_{j=1}^{5} z_j^{*2}}}$$

$$= \frac{0.1462\times1+0.1867\times1+0.0460\times1+0.1776\times1+0.0720\times1}{\sqrt{0.1462^2+0.1897^2+0.0460^2+0.1776^2+0.0720^2}\cdot\sqrt{1^2+1^2+1^2+1^2+1^2}}$$

$$= 0.90621$$

Similarly available: $\psi_2 = 0.93610, \psi_3 = 0.89452$, because $1 > \psi_2 > \psi_1 > \psi_3$, so the second scheme is better.

5. Conclusions

Based on the factors that affect the efficiency of the hub transfer, considering passenger satisfaction, transfer coordination, transfer efficiency, smoothness, economy, *etc*., a hub transfer program evaluation index system is established. A simple mathematical theory-vector cosine law is applied to complicated hub transfer program evaluation. Thereby, a multi-objective decision hub transfer scheme evaluation model based on cosine of the vector's angle is established. The model simplifies the evaluation process, is easy to understand, and makes it easier to check for errors. Moreover, a new method for the evaluation of urban transport interchange hub has been proposed, which formed a base for evaluating the hub transfer scheme.

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Author Contributions

Yao Liya responsible for inspection and modification the paper. Xia Xinfeng designed research. Yao Liya proposed recommendations. Xia Xinfeng performed research and analyzed the data, and she wrote and translated the paper. Yao Liya modified article language. Sun Lishan responsible for the modification of paper's English translation.

Conflicts of Interest

The authors declare no conflict of interest.

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