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Simulation-Based Optimization of Transport Efficiency of an Urban Rail Transit Network

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Abstract: It has been proven that developing urban rail transit (URT) is the key to solving the traffic problems in big cities, and transport efficiency is essential for scientific line planning and construction, operation management and sustainable development of urban rail transit. This paper focuses on the transport efficiency of the URT network and adopts shadow efficiency theory creatively to combine factors of passengers, capacity, and efficiency effectively. A quantitative calculation method of system utility based on "double time penalty" is proposed. According to the characteristics of Beijing URT, this paper puts forward a single optimization strategy and combinatorial optimization strategy and analyzes the results with DEA. The simulation of Beijing subway network proves the availability of the method and its optimization effects.

Keywords: urban rail transit; transport efficiency; network operation; optimization; simulation; DEA analysis

1. Introduction

Urban rail transit has become an important part of urban traffic, with the advantages of large capacity, high speed, low land occupation, energy conservation and environmental protection. The global scale of urban rail transit lines keeps rising, and China is at the climax of network construction. However, with the completion of some lines, not all rail transit systems can operate at high efficiency, and problems such as overcrowding of railway lines and transfer hubs are gradually emerging. Beijing subway, for example, reached 856.2 km in network operation length in 2021 and ranked second in the world, facing several typical problems, including insufficient network planning, overly conservative allocation of transport capacity, and prominent imbalance of passenger flow. An essential research priority is how to fully exploit the efficiency of transport services supplied by urban rail transit under network conditions and ensure its sound and quick development. It is also the basis for constructing a sustainable urban transport system, offering a theoretical foundation for improved scientific planning, cost savings, and better passenger service.

Literature Review and Innovation of This Paper

Scholars put forward the concept of transport efficiency based on economic efficiency. Costa et al. [1] mentioned that efficiency is the comparison between the realization and best level of output and input. Karlaftis et al. [2] pointed out that the technical efficiency of transport reflects the degree to which the maximum mileage and passenger transport output can be reached under the given labor, fuel and capital inputs, or the minimum input that can be used to output a given level. Zhang et al. [3] proposed that the transport efficiency of urban rail transit is the ratio of the effective output to the resource input. Lu [4] built up a three-level theory including capacity output efficiency, capacity utilization efficiency, and demand meeting efficiency. Holvad [5] thought that efficiency and productivity analysis can be used to determine the ability of entities to transform inputs into outputs. This paper holds that the transport efficiency of the urban rail transit network system refers to

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Citation: Wang, L.; Lu, F.; Han, B.; Zhang, Q.; Zhang, C. Simulation-Based Optimization of Transport Efficiency of an Urban Rail Transit Network. *Appl. Sci.* **2023**, *13*, 1471. https://doi.org/10.3390/app13031471

Received: 11 October 2022
Revised: 22 November 2022
Accepted: 11 January 2023
Published: 22 January 2023

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the relative relationship between the investment in building the system and the transport services provided to the public.

For research on the influencing factors of transport efficiency, the methods usually include qualitative analysis, Tobit method, multiple regression method, Stochastic Frontier Analysis (SFA) and panel regression, etc. Kapetanovic et al. [6] used the Tobit regression method and concluded that per capita GDP, population density, the existence of double/multi-track lines, and the percentage of electrified lines have significant positive effects on passenger transport efficiency. Catalano et al. [7] provides information about the frequency of occurrence of different input measures in efficiency studies for railways. Fitzová et al. [8] explored the determinants of public transport efficiency in the Czech Republic through the panel regression method. Fitzová et al. [9] used SFA and the bootstrap method to calculate transport efficiency and studied its influencing factors. Li et al. [10] considered the external environment and evaluated the bus operation efficiency of 30 central cities in China by the Tobit regression method. Alam et al. [11] evaluated the inter-annual technical efficiency of Pakistani railways and regarded railway efficiency as a function of internal and external factors. Ingvardson et al. [12] used multiple regression analysis to verify the prior hypothesis. Zhou et al. [13] put forward that the application of virtual marshaling technology can effectively improve the service level of urban rail transit. Yin et al. [14] discussed the characteristics of COVID-19 transmission and identified vulnerable areas to target to prevent and control the spread of the epidemic in rail transit. Zhao et al. [15] applied multilayer complex network theory to study the impacts that a newly built metro brought to a second-tier city.

There are many methods to evaluate transport efficiency, including multi-index comprehensive evaluation methods represented by the entropy weight method (EWM), the fuzzy comprehensive evaluation (FCE) method, technology for order preference by similarity to an ideal solution (TOPSIS), nonlinear statistical methods represented by a neural network, parametric methods represented by SFA, and mathematical programming methods represented by data envelopment analysis (DEA) and its derivatives, etc. Owais et al. [16] took the variance of PTN and the direct trip percentage as factors to evaluate the transfer efficiency in Cairo. Mallikarjun et al. [17] evaluated the operation performance of American rail transit and explored the reason for its inefficiency by using the non-oriented network DEA. Lobo et al. [18] used SFA to study the technical efficiency of 17 European metro systems. Sharma et al. [19] used a DEA analysis of efficiency with regard to Indian railways, comparing some 16 zones across the country. Marchetti et al. [20] provided particular methodological insights into the influence of the chosen frontier method on the obtained efficiency results in the case of railways using a meta-analysis approach. Lin et al. [21] explained the link between efficiency and effectiveness by DEA. Zhang et al. [22] evaluated the performance of the EWM–TOPSIS method considering four indicators including the global network efficiency. Huang et al. [23] provided a new method based on EWM–TOPSIS to evaluate railway transport efficiency. Yao et al. [24] evaluated the public transport efficiency of 11 cities in China by super-efficient network DEA. Ye et al. [25] decomposed the efficiency into pure technical efficiency and scale efficiency and studied the spatial difference of efficiency. Jiao et al. [26] constructed the matrix of "Operational Efficiency-Malmquist Index" to comprehensively compare the advantages and disadvantages of urban rail transit operational efficiency. Wey et al. [27] proposed a hybrid network data envelopment analysis (MNDEA) model with shared resources, a two-stage network and parallel structure integration. Reuben et al. [28] used the truncated regression two-stage bootstrap data envelopment analysis method to study the TOD development efficiency of Seoul transfer hub. Ravi et al. [29] benchmarked the performance of bus services in eight cities based on DEA. Wanke et al. [30] used stochastic data envelopment analysis (SDEA) and a Beta two-stage regression method to analyze different transportation modes in 285 cities from 2009 to 2012 and discussed their efficiency levels. Zhang et al. [31] established an index system consisting of 4 criteria and 24 indicators, covering key examination contents

of bus operating performance. Samet et al. [32] proposed a non-radial data envelopment analysis approach to measure operational and service efficiencies simultaneously.

One of the key components of urban rail transit efficiency is transfer efficiency, which includes the transfer within the system and the transfers between the urban rail system and other modes of transport. Sancha et al. [33] pointed out that the transfer efficiency of passengers is affected by the degree of automation in the stations, multiple traffic modes and long transfer distances. Reuben et al. [34] explored the efficiency of transit stations using a robust bootstrap Data Envelopment Analysis. Hernandez et al. [35] found that the three most important and potentially derivative transfer efficiency factors related to passengers include the impact on the comfort of the station's internal environment. Sadhukhan et al. [36] pointed out that rail transit transfer efficiency of different groups of passengers would be affected by their travel purpose and monthly household income. Zhang et al. [37] established a comprehensive evaluation model of transfer efficiency based on the IEM-Vague. Matsiuk et al. [38] constructed a discrete-event simulation model of the organization of transfer trains. Lee et al. [39] estimated the transfer efficiency by DEA and determined the factors affecting the efficiency by Tobit regression analysis. Zhou et al. [40] established a three-stage DEA evaluation index system for public rail transfer efficiency.

With many achievements made in the theoretical research of transport efficiency, however, few have focused on railway and urban rail transit systems. Some research on the transport efficiency of the railway network adopted complex network theory and did not fully consider the capacity constraints of traffic nodes. Other studies combined dynamic factors such as capacity changes, operation plans and passenger demand, but only focused on one or two influencing factors, lacking studies on the global change and the case analysis for the whole network, which cannot provide a reference for passengers or operating units. This paper provides an idea for the calculation and optimization of network transport efficiency by shadow capacity and simulation, which can provide systematic and scientific guidance for improving efficiency. Other scholars can refer to the ideas of this paper and conduct theoretical research on facilities coordination and train operation plans inside the hub, as well as study the connection and coordination between urban rail transit and land transport. It also has certain theoretical significance for the future research of comprehensive transportation systems.

It is very limited and unscientific to evaluate the final effect of efficiency only by the index system. No matter the total index or the average load index, it can't show the actual transport effect of the network system. However, the evaluation method based on global optimization is idealized, especially when considering the sharing relationship of the urban rail transit system in the whole transport system. This paper puts forward a theoretical framework of transport efficiency and the shadow efficiency method, explaining the relationship among capacity, passenger flow and efficiency. Shadow efficiency also reflects the different values of the same resource input in different parts of the network and can be used to analyze the rational allocation of resources. A quantitative calculation method of system utility based on "double time penalty" is proposed for the first time. Simulation research on the optimization strategy of network transport efficiency is proposed to fully reflect the interaction among various influencing factors, and simultaneously to study dynamic systems from time and space. The feasibility of the simulation experiment method has been proved by the actual case of Beijing subway network.

This paper is organized in the following way. Section 2 introduces the calculation method of transport efficiency. Section 3 presents the efficiency estimation method based on simulation. Section 4 discusses the experimental analysis method based on DEA. Section 5 is the conclusion of this paper and suggestions for future research.

2. Calculation Method of Transport Efficiency

2.1. Shadow Efficiency

Capacity (traffic supply) is an important foundation of efficiency research, and the matching relationship between capacity and passenger flow (traffic demand) is the key to efficiency. In order to quantitatively explain the relationship between capacity, passenger flow and efficiency, this paper refers to the concept of "shadow price" in economics and operational research for reference, and then introduces the new concept of "shadow efficiency" to explain the phenomenon of partial capacity improvement being inconsistent with overall efficiency improvement. In other words, shadow efficiency equals the variation value of the system's global utility, which is caused by the slight change in the individual unit capacity of a certain part of the urban rail transit system.

2.2. Double Time Penalty Method

1. System input

In order to quantitatively study the shadow efficiency, the input and output of the system must be calculated. The cost of the rail transit network, stations, vehicles, and vehicle kilometers is shown in Table 1:

Table 1. Cost of urban rail transit.

	Character	Unit Cost	Unit Conversion Cost
Network	Underground (CNY/km)	1,000,000,000	136,900
	Elevated (CNY/km)	300,000,000	41,000
Station	Underground (CNY/station)	200,000,000	27,300
	Elevated (CNY/vehicle)	100,000,000	13,600
Vehicle	Type A (CNY/vehicle)	12,000,000	1600
	Type B (CNY/vehicle)	8,000,000	1000
Running kilometer (CNY/vehicle kilometer)		-	16.74

Value description: the unit conversion cost of the network, station, and vehicle is calculated by multiplying its own unit cost by the annual interest rate of 5%. The total operating cost per running kilometer of each vehicle includes service cost, maintenance cost, and management cost. The time value is calculated according to the average wage in Beijing (CNY 36/hour), which means CNY 0.01/s.

2. System output

The main product provided by the urban rail transit system is the displacement of passengers. Passengers are most concerned about the number of passengers served by the system, the total travel time spent on rail transit, the reliability of arrival time, and other service quality indicators such as safety and comfort. Since a high level of punctuality and safety of urban rail transit under normal circumstances has been realized, and it is difficult to determine the comfort index, this paper focuses on the number of passengers transported by the system and the total travel time of passengers. When the number of passengers served is large and the total travel time is short, a new method is required to take the two indexes into account comprehensively.

Generally speaking, urban rail transit has the most direct competition and substitution relationship with traditional public transport on the ground. The newly attracted passenger flow of urban rail transit is mainly transferred from buses (at present, the effect of attracting passenger flow from passenger cars is relatively limited in China). According to relevant research, the average travel speed of buses in big cities in China is only 15–18 km/h, while the average travel speed of urban rail transit can reach 30–35 km/h. It can be considered that a subway train travels at roughly twice the speed of buses. In other words, if a passenger abandons rail transit and opts for land transport, the travel time may be doubled.

Based on the above analysis, this paper proposes that when some passengers of the urban rail transit system give up using rail transit because of capacity limitation, operation

interruption or other reasons, their travel time should be doubled, which is called "double time penalty". The "double time penalty method" is used in this paper to calculate total travel time, which solves the problem of two unified indexes by converting the number of people into travel time. The "total travel time savings" obtained by passengers can be regarded as the total utility provided by the urban rail transit network system to passengers.

The specific method for calculating the total travel time by the "double time penalty method" is as follows:

$$T_{total} = \sum T_s + \sum T_p \quad (1)$$

where T_{total} is the total travel time generated by transport services provided by the system, and $\sum T_s$ is the travel time of passengers who are served by the system.

$\sum T_p$ is the travel time of passengers who should have been served but did not, which can be calculated by:

$$\sum T_p = \sum t \cdot 2 \quad (2)$$

where t is the Actual travel time of the same OD passengers in the rail network.

3. Simulation Model

3.1. Simulation System

According to the calculation method of network transport efficiency defined above, the corresponding data should be collected to calculate the network efficiency under different schemes. However, considering the difficulty in collecting the huge amount of data, the method of passenger flow simulation is adopted to obtain the maximum network efficiency under different scheme input conditions. Accordingly, this study builds a simulation test system of urban rail transit operation based on the idea of multi-agent, thereby modeling the operation and interaction mechanism of passengers, trains, and network, and simulating the operation under different network topologies, train operation plans and passenger flow organizations, as well as output statistical indicators. The output diagram of the simulation is shown in Figure 1.

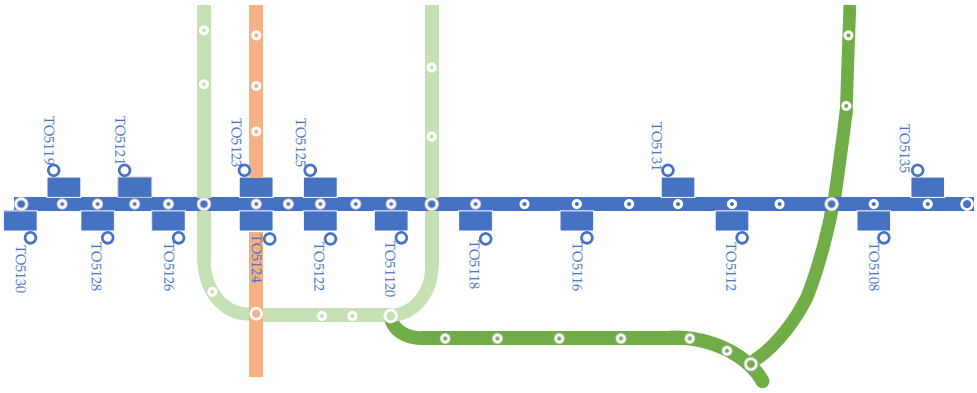


Figure 1. The interface of train simulation results.

3.2. Experimental Design

The "Urban Rail Transit Network Passenger Flow Simulation Experimental Platform" can be used to optimize and adjust the network structure, line attributes, station attributes, train plans, passenger arrival rules, and other aspects of urban rail transit in order to study the relationship between the operational efficiency of an urban rail transit network and its influencing factors and to explore the effectiveness and practical efficiency of optimization methods. The efficiency of optimization can be evaluated by simulating networks in specific scenarios and comparing passenger journey times before and after optimization.

3.2.1. Simulation Experiment Design for Line Construction

Different orders of line construction will have different effects on the network forms and passenger flow distribution, affecting the efficiency of network operation. The experimental scene of constructing a new line in the existing rail network is designed by following the steps below:

Step 1: Several lines in the rail network are selected as the research objects and recorded as "lines to be built" $\{L_1, L_2, \ldots, L_n\}$.

Step 2: The above lines are deleted in the network topology diagram, and the input and output passenger volume of each station are transferred to nearby stations in a certain proportion, as shown in the following formulas.

$$P'^{t}_{i,j} = \alpha^{t}_{i,j} \cdot P^{t}_{i} \tag{3}$$

$$0 \leq \sum_{j=1}^{m^{t}_{i}} \alpha^{t}_{i,j} \leq 1 \tag{4}$$

where $P'^{t}_{i,j}$ is the transfer passenger flow of the alternative station j of station i on line t; P^{t}_{i} is the original inbound or outbound volume of station i on line t (the transfer probability of input and output volume can be the same or different according to the actual situation); $\alpha^{t}_{i,j}$ is the transfer ratio; m^{t}_{i} is the number of alternative stations for station i on line t. The proportion of transferred passenger flow needs to be determined according to the actual situation.

When the total transfer ratio is less than 1, it is equivalent to the loss of the surplus passenger flow. After the completion of the line, the induced passenger flow ratio can be calculated as follows:

$$\beta^{t}_{i} = 1 - \sum_{j=1}^{m^{t}_{i}} \alpha^{t}_{i,j} \tag{5}$$

Step 3: The passenger flow simulation is carried out on the rail network after deleting the "lines to be built", and the passenger travel time of the required period and OD is counted, which is recorded as T0. This scheme is regarded as the "benchmark scheme".

Step 4: According to the order of experimental design, the lines in the "lines to be built" are added in turn, and the passenger travel time is separately counted and recorded as $T(1) = \{T_1, T_2, \cdots, T_n\}$, as the first set of statistical results. Designing multiple sets of construction sequences will produce multiple sets of experimental data $T(1)$, $T(2)$, ... , $T(m)$.

Step 5: Comparison is made among $T(1)$, $T(2)$, ... , $T(m)$, and the simulation results are analyzed.

A single optimization simulation experiment based on the 2015 Beijing urban rail transit network is carried out based on the above experimental designs. Firstly, Line 6 and the Changping Line are removed simultaneously as a benchmark scheme, and the passenger flow of each station of the two lines is transferred to the surrounding alternative stations according to a certain proportion. Then, Line 6 and the Changping Line are removed, respectively, the former corresponding to the construction of the Changping Line first, and the latter to the construction of Line 6 first, based on the benchmark scenario. The transferred stations and corresponding proportions are shown in Tables 2 and 3.

Table 2. Replacement station and proportion of passenger flow in Line 6.

Removed Station	Replacement Station—Line	Replacement Ratio	Loss Ratio
Haidianwuluju	Cishousi—10	0.6	0.4
Cishousi	Cishousi—10	0.8	0.2
Huayuanqiao	Cishousi—10	0.6	0.4
Baishiqiao South	Baishiqiao South—9	0.8	0.2
Chegongzhuang West	Baishiqiao South—9 Chegongzhuang—2	0.3 0.3	0.4
Chegongzhuang	Chegongzhuang—2	0.8	0.2
Ping'anli	Ping'anli—4	0.8	0.2
Beihaibei	Ping'anli—4 Nanluoguxiang—8	0.3 0.3	0.4
Nanluoguxiang	Nanluoguxiang—8	0.8	0.2
Dongsi	Dongsi—5	0.8	0.2
Chaoyangmen	Chaoyangmen—2	0.8	0.2
Dongdaqiao	Chaoyangmen—2 Hujialou—10	0.3 0.3	0.4
Hujialou	Hujialou—10	0.8	0.2
Jintailu	Jintailu—14	0.8	0.2
Shilibao	Jintailu—14	0.6	0.4
Qingnianlu	Jintailu—14	0.4	0.6
Dalianpo	Jintailu—14	0.2	0.8
Huangqu	Jintailu—14	0.1	0.9
Changying	Jintailu—14	0.1	0.9

Table 3. Replacement station and proportion of passenger flow in the Changping Line.

Removed Station	Replacement Station—Line	Replacement Ratio	Loss Ratio
Xi'erqi	Xi'erqi—13	0.8	0.2
Shengming Kexueyuan	Xi'erqi—13 Zhuxinzhuang—8	0.5 0.3	0.2
Zhuxinzhuang	Zhuxinzhuang—8	0.8	0.2
Gonghuacheng	Zhuxinzhuang—8 Xi'erqi—13	0.3 0.3	0.4
Shahe	Zhuxinzhuang—8 Xi'erqi—13	0.3 0.3	0.4
Shahe University Park	Zhuxinzhuang—8 Xi'erqi—13	0.3 0.3	0.4
Nanshao	Zhuxinzhuang—8 Xi'erqi—13	0.3 0.3	0.4
Beishaowa	Zhuxinzhuang—8 Xi'erqi—13	0.3 0.3	0.4
Changping Dongguan	Zhuxinzhuang—8 Xi'erqi—13	0.3 0.3	0.4
Changping	Zhuxinzhuang—8 Xi'erqi—13	0.3 0.3	0.4
Shisanling Jingqu	Zhuxinzhuang—8 Xi'erqi—13	0.3 0.3	0.4
Changping Xishankou	Zhuxinzhuang—8 Xi'erqi—13	0.3 0.3	0.4

The passenger travel time during morning rush hour for the three simulation experiments are counted as shown in Table 4.

Table 4. Simulation results of line construction sequence.

Experimental Scheme	Experiment Description	Passenger Travel Time/s	Passenger Flow/Person	Per Capita Travel Time/s
Deletion of Line 6 and Changping Line	Benchmark scheme	2,381,165,013	1,103,809	2157.226
Deletion of Line 6	Construction of Changping Line first	2,524,073,485	1,155,816	2183.802
Deletion of Changping Line	Construction of Line 6 first	2,711,012,551	1,246,594	2174.736

The passenger flow of the "Deletion of the Changping Line" scheme, which is the largest in the network, is used as the standard in order to calculate the shadow efficiency of the above three schemes in a unified manner, and fewer passengers transported by the other two schemes are considered as the loss passenger flow, whose travel time needs to be doubled. The transport efficiency of the three scenarios is shown in Table 5 below, where the inputs and outputs (travel time saving) are calculated as a uniform fee.

Table 5. Transport Efficiency calculation of line construction sequence.

Experimental Scheme	Increased Input/CNY	Penalty Travel Time/s	Travel Time Saving/CNY	Transport Efficiency
Deletion of Line 6 and the Changping Line	-	2,997,204,042	-	-
Deletion of Line 6	1,632,890	2,920,555,841	766,482	0.469
Deletion of the Changping Line	7,259,660	2,711,012,551	2,861,914	0.394

Although it can be seen from Table 5 that the shadow efficiency of both schemes is less than 1, "Deletion of Line 6" and "Deletion of the Changping Line" are feasible considering the higher interest rate of the loan, which increases the cost. Additionally, there is not a significant difference in shadow efficiencies between the two schemes, suggesting that the two lines have similar construction priorities. As an at-grade line with a shorter mileage and cheaper investment cost than Line 6, the Changping Line is more efficient to construct first. In terms of passenger flow, the penalty travel time for lost passengers of the Changping Line is higher because there is no alternative line.

3.2.2. Simulation Experiment Design for Change of Train Operation Plans

Train departure interval and train formation can be flexibly adjusted in the operation stage. The simulation experiments are designed as follows:

Step1: The lines in need of adjusting departure interval and marshaling are selected as the research object.

Step2: The marshaling and capacity of subway lines are adjusted in the train information attribute of the input database.

Step3: The train departure interval is directly adjusted by translating the running line in the simulation interface.

Step4: The network passenger flow is simulated and the passenger travel time is counted.

Step5: Compared with the original scheme, the simulation results are analyzed.

3.3. Simulation Experiment Parameters Setting

The simulation experiment is implemented on Beijing rail transit to explore the influence of various factors on network operation efficiency.

The main features and problems of Beijing subway are as follows: (1) the continuous growth of network passenger volume has led to a sudden increase of pressure on operation and management departments; (2) the unreasonable layout of Beijing's urban functions is

the main reason for the huge pressure on Beijing subway passenger flow; (3) the planning of Beijing subway network is insufficient; (4) the existing transport capacity allocation of Beijing subway trunk lines is too conservative; (5) the imbalance of passenger flow is very prominent; (6) the network transfers are at a large number; (7) the railway organization mode is single and the transfer is inconvenient; (8) the service level is not high because of the great influence between different parts of the network.

Combined with the characteristics of the Beijing subway network, it can be considered that there are three main factors that have a great influence, namely, network scale, train departure density and passenger flow scale. By setting different levels of the three factors and combining them with each other, several experimental schemes can be obtained. These experimental schemes are simulated and compared, respectively, and the effects and adaptability of different optimization strategies are analyzed.

1. Rail network scale

Based on the urban rail transit network of Beijing in 2015 and referring to the simulation experiment of the line construction sequence, Line 6 and the Changping Line are selected as the lines to be built. The simulation scenarios are set as shown in Table 4, and "Original rail network" means the largest network scale after the construction of the Changping Line and Line 6.

2. Train departure density scale

Beijing subway Line 2, as a loop line, plays the role of dispersing the transfer passenger flow and relieving the transfer pressure. The adjustment of the departure density of Line 2 has a significant impact on the whole rail network. The simulation scenarios are set as follows.

- "Original" means that the departure density of Line 2 remains unchanged.
- "Increased by 30 s" means that the departure interval of Line 2 in the up and down direction from 7:00 to 9:00 during morning rush hours will be extended for 30 s, and the departure interval will remain unchanged in other periods.

3. Network passenger flow scale

Different rail network scales and departure densities are suitable for different passenger flow scales. To explore the matching relationship between supply and demand, the simulation scenarios are set up as follows.

- "Increased by 10%" means the input passenger flow of all stations in the whole rail network will increase by 10% at the same time. This scenario serves as the benchmark passenger flow. All passengers in this scene are regarded as the potential passenger demand of urban rail transit, and the reduced passenger flow in other schemes is the lost passenger flow.
- "Decreased by 30 s" means that the inbound passenger flow of all stations in the whole rail network will be reduced by 10% at the same time.

4. Combined experimental schemes

Different schemes are combined to obtain the following 24 experimental schemes after setting the scheme parameters of various factors, as shown in Table 6.

Table 6. Simulation scheme of hybrid optimization strategy.

Rail Network Scale	Train Departure Density Scale	Network Passenger Flow Scale	Scheme Number
Original rail network	original	original	1
		increased by 10%	2
		decreased by 10%	3
	increased by 30 s	original	4
		increased by 10%	5
		decreased by 10%	6
Deletion of Line 6 and the Changping Line	original	original	7
		increased by 10%	8
		decreased by 10%	9
	increased by 30 s	original	10
		increased by 10%	11
		decreased by 10%	12
Deletion of Line 6	original	original	13
		increased by 10%	14
		decreased by 10%	15
	increased by 30 s	original	16
		increased by 10%	17
		decreased by 10%	18
Deletion of the Changping Line	original	original	19
		increased by 10%	20
		decreased by 10%	21
	increased by 30 s	original	22
		increased by 10%	23
		decreased by 10%	24

3.4. Simulation Results

The 24 schemes in Table 6 are simulated, and the travel time and passenger flow volumes of the whole rail network in morning rush hours are counted, respectively, as shown in Table 7.

Table 7. Simulation results of hybrid optimization strategy.

Scheme Number	Morning Peak Passenger Flow/Person	Peak Passenger Travel Time/s	Per Capita Travel Time/s
1	1,298,994	2,854,821,723	2197.717
2	1,426,503	3,151,757,493	2209.429
3	1,171,679	2,571,171,388	2194.433
4	1,292,552	2,844,934,820	2201.022
5	1,419,809	3,161,789,427	2226.912
6	1,164,728	2,553,327,123	2192.209
7	1,132,866	2,381,165,013	2101.895
8	1,243,306	2,622,424,077	2109.235
9	1,021,872	2,150,801,875	2104.766
10	1,125,714	2,380,704,062	2114.839
11	1,234,272	2,622,812,667	2124.988
12	1,014,728	2,135,984,173	2104.982
13	1,177,913	2,524,073,485	2142.835
14	1,293,496	2,792,749,274	2159.071
15	1,062,801	2,273,367,855	2139.034
16	1,170,959	2,523,531,092	2155.098
17	1,284,898	2,793,521,875	2174.121
18	1,056,425	2,259,240,766	2138.572
19	1,254,250	2,711,012,551	2161.461
20	1,377,168	2,981,616,485	2165.035
21	1,131,075	2,444,896,738	2161.569
22	1,247,615	2,698,081,428	2162.591
23	1,370,535	2,989,992,581	2181.624
24	1,124,645	2,427,609,731	2158.556

4. Result Analysis

4.1. Experimental Analysis Based on DEA

DEA is a mathematical programming method to evaluate the relative efficiency between decision-making units with multiple inputs and outputs. The mathematical programming model is used to evaluate the relative efficiency (DEA efficient) between "departments" or "units" with multiple inputs, especially multiple outputs. Judging whether the decision-making unit (DMU) is DEA efficient according to the observed data of each DMU is essentially determining whether DMU is located on the "production frontier" of the production possibility set, which is an extension of the production function to a multi-output situation in economics. DEA can be thought of as a nonparametric statistical estimation method since it can be used to determine the structure, characteristics, and construction method of the production frontier. According to DEA methods, models, and theories, we can directly use input and output data to establish a nonparametric DEA model for economic analysis because DEA has a natural economic background. The steps of the DEA evaluation method are shown in Figure 2.

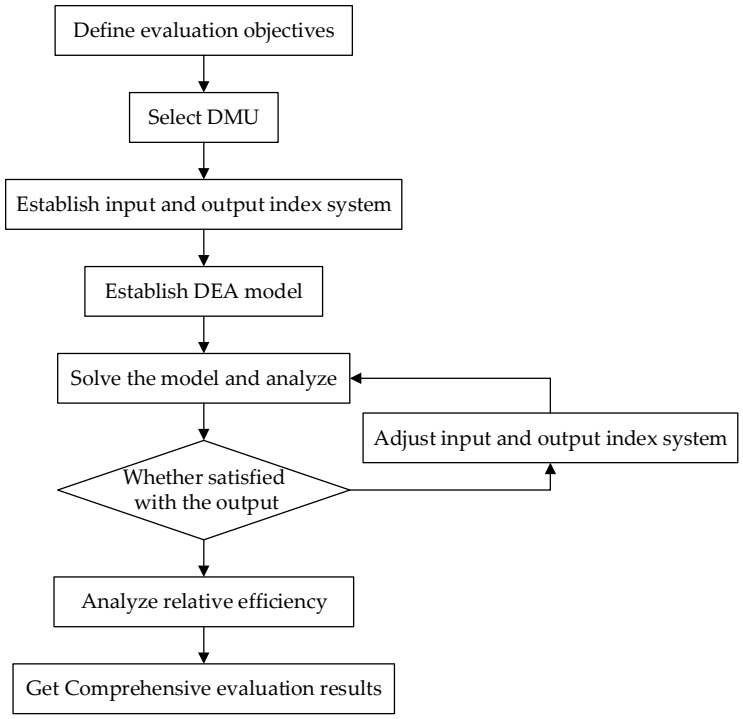


Figure 2. The flowchart of the DEA.

When using the DEA method to analyze the simulation results of the combinatorial optimization strategy, DMU must be determined first. DMU refers to each rail transit network with different combination optimization strategies in this paper. According to the characteristics of the combinatorial optimization strategy, the input index system is established, and the output index system is the only index of the generalized travel time. All indexes are input into DEA software, and the output results of the model are obtained. The most effective combination of optimization strategies should be determined based on the output results. If the combination is found to be invalid, the main reasons should be investigated before attempting to identify the strongest combination rule among optimization strategies.

4.2. DEA Analysis of Simulation Results

When using the DEA method to evaluate the network transport efficiency after compound optimization, it is necessary to first determine the input and output index of each DMU, which is set to 24 experimental schemes.

The most basic inputs of urban rail transit are the length of the line, the number of stations and vehicles, and the vehicle kilometers affected by the operation plan. According to the previous analysis, the important output of network transport efficiency is the travel time saved by passengers. The input and output indicators of the DEA method are shown in Table 8.

Table 8. DEA Input-output of Network Transport Efficiency.

	Name	Index
Input	X1	number of vehicles (vehicle)
	X2	number of stations (station)
	X3	length of operating lines (km)
	X4	kilometers of train operation (vehicle kilometer)
Output	Y	travel time saving (s)

Among the 24 schemes, the scale of passenger flow can be classified into three levels: original passenger flow, a 10% reduction in passenger flow and a 10% increase in passenger flow which, respectively, represent three periods of the rail transit network. The DEA model is used to evaluate different schemes at the three levels, and the adaptability of different rail network scales and capacity levels to the passenger flow scale is analyzed.

1. DEA evaluation of original passenger flow scale

The schemes under the original passenger flow scale include schemes 1, 4, 7, 10, 13, 16, 19 and 22, and the DEA evaluation results, and calculated network efficiency are shown in Table 9 below. Scheme 10 is the benchmark scheme, that is, the Changping Line and Line 6 are deleted, and the departure intervals of Line 2 during morning rush hours are increased by 30 s.

Table 9. DEA evaluation results of each program for the original passenger flow scale.

DEA Evaluation Results					Network Efficiency		
Optimum Scheme	**Technical Efficiency**	**Pure Technical Efficiency**	**Scale Efficiency**	**Scale Reward**	**Input [1]**	**Output [2]**	**Shadow Efficiency**
1	1	1	1	unchanged	11,310,210	2,376,650	0.21013
4	0.975696	1	0.975696	decreased by degrees	11,273,050	2,183,510	0.19369
7	0.759642	1	0.759642	decreased by degrees	37,162.8	373,910	10.06150
10	0.685759	1	0.685759	decreased by degrees	0	0	-
13	0.792031	0.998691	0.793069	increased by degrees	4,686,273	634,960	0.13549
16	0.723491	1	0.723491	decreased by degrees	4,649,110	279,680	0.06015
19	0.98784	1	0.98784	decreased by degrees	6,661,103	1,972,950	0.29619
22	0.958522	1	0.958522	decreased by degrees	6,623,940	1,811,400	0.27346

[1] The input refers to the increased cost (unit: CNY) compared with the benchmark scheme. [2] The output refers to the saved travel time (unit: CNY) compared with the benchmark scheme.

The first column in Table 9 is the decision-making unit, and the second, third and fourth columns are technical efficiency, pure technical efficiency and scale efficiency, respectively. There is a certain correlation among them: scale efficiency = technical efficiency/pure technical efficiency. Through these three indicators, the technical efficiency and scale efficiency of the object to be studied can be explained. The last column is the scale reward. It can be seen that the scale reward of scheme 1 (original rail network, original departure density and original passenger flow scale) remains unchanged, while the scale reward of scheme 13 (deleting Line 6/constructing the Changping Line, original departure density and original passenger flow scale) increases, and the rest of the schemes decrease.

The pure technical efficiency of other schemes, except scheme 13 is 1, which means the utilization rate of various inputs has reached the optimal value, and there is no waste phenomenon. If the inputs are increased, waste will be generated, resulting in a decrease in the scale efficiency of the rail network. However, the pure technical efficiency of scheme 13 is less than 1, which indicates that at the current technical level, the input scale is low and the transport efficiency of the rail network cannot be fully exerted. Therefore, some inputs can be correspondingly increased to improve the output, thus improving the transport efficiency of the rail network, that is, the scale efficiency is increasing.

Comparing scheme 13 with scheme 16 (original passenger flow, deletion of Line 6, an increase of 30 s in the morning peak departure interval of Line 2), it can be seen that under the same passenger flow level and rail network scale, the train departure intervals become the bottleneck of network transport efficiency. When the departure interval is small (departure density is high) and the transport capacity is large, the network transport efficiency is higher. Therefore, higher departure density should be allocated to give full play to the efficiency of the rail network scale when necessary.

2. DEA evaluation results of an increasing passenger flow scale by 10%

The schemes under the scale of increasing passenger flow by 10% include schemes 2, 5, 8, 11, 14, 17, 20 and 23, and the DEA evaluation results and calculated network efficiency are shown in Table 10 below. Scheme 11 is the benchmark scheme, that is, the Changping Line and Line 6 are deleted, and the departure intervals of Line 2 during morning rush hours are increased by 30 s.

Table 10. DEA evaluation results of each program for a 10% increase in passenger flow scale.

Optimum Scheme	DEA Evaluation Results			Scale Reward	Network Efficiency		
	Technical Efficiency	Pure Technical Efficiency	Scale Efficiency		Input [1]	Output [2]	Shadow Efficiency
2	1	1	1	unchanged	11,310,210	2,880,320	0.25466
5	0.961627	1	0.961627	decreased by degrees	11,273,050	2,481,860	0.22015
8	0.823666	1	0.823666	decreased by degrees	37,162.8	445,540	11.98905
11	0.762984	1	0.762984	decreased by degrees	0	0	-
14	0.841672	0.998505	0.842932	increased by degrees	4,686,273	726,970	0.15512
17	0.785603	1	0.785603	decreased by degrees	4,649,110	305,350	0.06567
20	1	1	1	unchanged	6,661,103	2,445,490	0.36713
23	0.952581	1	0.952581	decreased by degrees	6,623,940	2,055,940	0.31038

[1] The input refers to the increased cost (unit: CNY) compared with the benchmark scheme. [2] The output refers to the saved travel time (unit: CNY) compared with the benchmark scheme.

As can be seen from the above table, the scale reward of scheme 2 (original rail network, original departure density and a 10% increase in passenger flow scale) and scheme 20 (deleting the Changping Line/constructing Line 6, original departure density and increasing passenger flow scale by 10%) is unchanged, while the scale reward of scheme 14 (deleting Line 6/constructing the Changping Line, original departure density and increasing passenger flow scale by 10%) is increasing, and the scale rewards of the rest of the schemes decrease gradually.

3. DEA evaluation results of decreasing passenger flow scale by 10%

The schemes under the scale of decreasing passenger flow by 10% include schemes 3, 6, 9, 12, 15, 18, 21 and 24, and the DEA evaluation results and calculated network efficiency are shown in Table 11 below. Scheme 12 is the benchmark scheme, that is, the Changping Line and Line 6 are deleted, and the departure intervals of Line 2 during morning rush hours are increased by 30 s.

Table 11. DEA evaluation results of each program for a 10% decrease in passenger flow scale.

DEA Evaluation Results					Network Efficiency		
Optimum Scheme	Technical Efficiency	Pure Technical Efficiency	Scale Efficiency	Scale Reward	Input [1]	Output [2]	Shadow Efficiency
3	1	1	1	unchanged	11,310,210	1,799,820	0.15913
6	0.971652	1	0.971652	decreased by degrees	11,273,050	1,684,830	0.14945
9	0.542965	1	0.542965	decreased by degrees	37,162.8	154,330	4.15283
12	0.485527	1	0.485527	decreased by degrees	0	0	-
15	0.620231	0.999822	0.620342	increased by degrees	4,686,273	402,320	0.08585
18	0.573691	1	0.573691	decreased by degrees	4,649,110	274,240	0.05898
21	0.949969	1	0.949969	decreased by degrees	6,661,103	1,474,690	0.22138
24	0.92026	1	0.92026	decreased by degrees	6,623,940	1,387,770	0.20950

[1] The input refers to the increased cost (unit: CNY) compared with the benchmark scheme. [2] The output refers to the saved travel time (unit: CNY) compared with the benchmark scheme.

As can be seen from the above table, the scale reward of scheme 3 (original rail network, original departure density, and a 10% reduction of passenger flow scale) remains unchanged, while that of scheme 15 (deleting Line 6/constructing the Changping Line, original departure density and a 10% reduction of passenger flow scale) increases, and other schemes decrease.

4.3. Analysis Conclusion

To sum up, the following conclusions can be drawn:

(1) A small change in passenger flow has no significant impact on the per capita travel time of passengers.
(2) The shadow efficiency of increasing the departure density of crowded lines in morning rush hour is the highest, far exceeding that of other schemes, so it should be adopted first.
(3) The greater the passenger volume, the more obvious the efficiency improvement brought by increasing the departure density.
(4) The departure interval is the restriction of technical efficiency in the combination strategy, which can be increased to optimize the technical efficiency of all schemes.
(5) The newly built Line 6 can improve the scale efficiency of the system.
(6) The newly built Changping Line cannot improve the scale efficiency of the system.
(7) In combination optimization, under the conditions of original passenger flow and original departure interval, the shadow efficiency of the two schemes of removing the Changping Line and Line 6 is inconsistent with that of the single factor simulation experiment, and the relationship between shadow efficiencies also changes, which proves that the shadow efficiency is marginal efficiency, which is related to the starting point of the original scheme.
(8) According to the current cost calculation methods and parameter values, the cost of Beijing subway lines accounts for the vast majority of the total cost, which has a great influence on the final calculation and evaluation results of efficiency.

It can be further concluded from the simulation results that the expensive construction cost of Beijing subway is an important factor that restricts the improvement of network transport efficiency. We should try our best to control the cost of newly built lines, so as to improve the passenger service level by providing a larger-scale rail network under the constraint of a certain efficiency level. Compared with the fixed costs such as the construction costs, the variable cost such as running kilometer is low, which means that the existing line capacity should be brought into full play. For example, passenger service level and transport efficiency can be improved by increasing the marshaling and shortening the departure interval. Last but not least, compared with the relatively expensive infrastructure reconstruction scheme, operation organizations with less investment should be given priority to improve transport capacity and efficiency.

5. Conclusions and Future Research

From the background of the rapid development of the urban rail transit network, this paper proposes the transport efficiency theory of the urban rail transit network system. It studies the interaction mechanism between capacity, passenger flow and efficiency, puts forward the shadow efficiency theory to express the quantitative relationship among them, and proposes a quantitative calculation method of system utility based on "double time penalty". The simulation experiments of single optimization strategy and combinatorial optimization strategy using DEA are designed, and the availability of these methods is proved by the case of the Beijing subway, and some optimization strategy combination rules are summarized. The results show that the departure interval is the restriction of technical efficiency, and the efficiency improvement brought by increasing departure density is more obvious with the increase in passenger volume. Improved departure density should be given priority to apply to crowded subway lines in morning peak hours, so as to boost the efficiency of the rail network. The cost of line construction contributes a large proportion of the total cost of Beijing subway, so we should give full play to the existing line capacity and give priority to changing operation organization to improve transport efficiency. The cost of newly built lines should be controlled, and the appropriate line system should be selected according to the function and passenger flow, to form an appropriate capacity supply and improve passenger service level under the constraint of a certain efficiency level. It is considered that the existing Beijing subway network can still improve the scale efficiency of the whole network system by adding new lines. However, attention should be paid to the hierarchy of lines and the upper limit.

There are still some aspects to be extended in future work. Firstly, although a large amount of actual data of the Beijing subway are applied, some parameters are simplified in the simulation experiments, which need to be more detailed and accurate to be used in practical work. Secondly, this paper only studies the transport efficiency of the system during rush hours under normal conditions. We should further consider the transport efficiency under abnormal conditions such as operation interruption and large numbers of passengers, as well as how to save the input of transport resources and improve transport efficiency during off-peak hours. In addition, considering the historical evolution of cities and networks, how efficiency evolves over a long period of time is also worthy of in-depth study.

Author Contributions: Conceptualization, L.W. and F.L.; methodology, L.W. and B.H.; software, L.W., F.L. and C.Z.; validation, L.W. and Q.Z.; formal analysis, L.W. and F.L.; data curation, F.L. and B.H.; writing—original draft preparation, L.W., F.L. and B.H.; writing—review and editing, L.W. and F.L.; funding acquisition, Q.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Beijing Natural Science Foundation (L201013).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: The authors thank everyone who contributed to this article.

Conflicts of Interest: The authors declare no conflict of interest.

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