A Research on Energy Efficiency Measurement of Urban Rail Transit Based on Dynamic DEA Model

Feng Zongbao¹, Liu Yang*, Wu Xianguo¹

¹ School of Civil Engineering & Mechanics, Huazhong University of Science & Technology, Wuhan 430074, China
* Wuhan University, Zhongnan Hospital of Wuhan University, Wuhan 430071, P.R. China

E-mail:18162591997@163.com

Abstract: With the accelerated construction process of urban rail transit, it brings much consumption of energy. While the energy of our country is not enough, it is of great meaning to improve the energy efficiency for the energy saving of the urban rail transit industry. In this thesis, data envelopment analysis (DEA) is used to construct the dynamic DEA model of energy input and output in different periods of subway lines, and quantitative analysis of urban rail transit energy efficiency. Based on the data of energy input and output in different periods of Wuhan Metro's existing operation lines, this thesis analyzes the utilization status of Wuhan Metro energy from three aspects: technical efficiency, scale efficiency and comprehensive efficiency, gaining the energy efficiency, and then measuring the dynamic energy efficiency through taking into time consideration. And on the basic of it, combining the slack variable adjustment values of each decision-making unit, it uses the difference between the adjustment value of the slack variable and the target value to identify the main influencing factors, and then providing an effective improvement strategy for the improvement of energy efficiency of different lines of Wuhan Metro.

Introduction
With the development of urbanization, the rail transit industry is also developing rapidly. Urban rail transit brings great convenience to citizens' travel, and it also brings about a rapid increase in energy consumption. However, China is a country with relatively few energy sources. Therefore, with the relatively scarce energy and the increasing attention to environmental protection, the improvement of energy efficiency is of great significance to the energy conservation of our rail transit industry.

In terms of energy efficiency measurement, traditional energy efficiency is to calculate single factor energy efficiency. However, whether traditional indicators based on the single factor productivity framework measure "efficiency" is worthy of scrutiny[1]. Based on the total factor productivity framework, Hu Jinli and Wang Shihchuan (2006) defined the total factor energy efficiency index, making up for the shortcomings of traditional indicators considering only the single element of energy[2]. In the total factor energy efficiency measurement method, some scholars have proposed the stochastic frontier production function method (SFA) and data envelopment analysis (DEA).

Based on data by mathematical programming model, the DEA method is a non-parametric method for determining the weight of input-output variables, which is not subject to subjective factors. This method is simple and practical. Recently, many domestic scholars have used this method to measure energy efficiency of total factors. Therefore, this paper will combine the relevant theories of DEA to
construct the model of urban rail transit energy input and output, and take the existing operation line of Wuhan Metro as an example, first adopt the DEC BCC model, from technical efficiency, scale efficiency and comprehensive efficiency. This thesis analyzes the current status of energy utilization of Wuhan Metro lines, and then combines the dynamic DEA model for comprehensive evaluation, and proposes an improvement strategy for the improvement of energy efficiency utilization of Wuhan Metro.

1 The method of dynamic DEA
DEA is short for data envelopment analysis, jointly proposed by A. Charnes, W. W. Cooper et al in 1978, which is a nonparametric method for measuring the relative effectiveness of production decision units with the same production properties, the same inputs, and the same output [3]. Its essence is to first construct a production front through the model, and then compare the input and output data of each decision unit with the production front. If the production unit falls on the production front surface, the DEA is valid, otherwise invalid [4].

In the development of the DEA method, it has been many different models. In order to avoid some shortcomings of the traditional DEA model, some scholars have introduced the DEA cross-efficiency model. Sun Wei, Wang Kunyan et al (2015) have used the DEA cross-efficiency model based on quadratic objective function to evaluate and analyze the economic benefits of public infrastructure in 35 large and medium-sized cities in China in 2012 [5]. However, most of the above DEA methods only have horizontal comparisons and lack of vertical comparisons, which cannot reflect the evaluation values of different decision-making units at different time points [6].

Based on the traditional DEA, the dynamic DEA model introduces time variables and constructs a multi-objective dynamic evaluation model including indicators, schemes and time, which can dynamically evaluate the created models. Some scholars have done some research and achieved certain results. Wang Weilin (2008) introduced appropriate dynamic DEA model to evaluate the comprehensive efficiency of regional circular economy development, fully evaluate and prioritize decision-making units. The energy input and output of Wuhan Metro is a dynamic process. Therefore, based on the traditional DEA model, this paper will use the dynamic DEA model to comprehensively evaluate the energy efficiency of urban rail transit.

2 Construction of energy efficiency measurement model for rail transit

2.1 Selection of input and output indicators
When taking the method of DEA to measure the energy efficiency of urban rail transit, determining the input and output indicators is the key to the effectiveness of the model. This paper takes into account the actual situation of rail transit energy utilization and the availability of data. The two indicators of electricity consumption and water consumption are used as input indicators, and the passenger flow and running mileage are used as output indicators.

2.2 Establishment of dynamic DEA model for energy efficiency measurement of rail transit
Based on the traditional DEA, the dynamic DEA model introduces time variables and constructs a multi-objective dynamic evaluation model including indicators, schemes and time, which can dynamically evaluate the created models. This thesis establishes the dynamic model of urban rail transit energy input and output, first adopting the traditional DEA output-based BCC model to evaluate the relative effectiveness of rail transit energy efficiency, seeing formula (1). And then according to the efficiency evaluation value of each decision unit in each time period, which are \( \theta_i^{(t)} \) (t=1, 2, ..., T; i=1, 2, ..., n), T-dimensional vector is established based on \( \theta_i^{(t)} \leq 1 \) and the decision unit is more efficient in each period, and it is regarded as the new DEA with only output, then the dynamic DEA is converted to the DEA with only output, seeing formula (2).

\[
\min \left[ \theta - \varepsilon \left( \sum_{i=1}^{m} s^- + \sum_{i=1}^{r} s^+ \right) \right]
\]
In the formula (1), "$n$" is relative efficiency; "$m$" is number of decision units; "$r$" is number of input indicators; "$v$" is number of output indicators; "$λ_i$" is weight coefficient of each decision unit; $x_i = [x_{i1}, x_{i2}]$, $x_{i1}, x_{i2}$ represents the electricity consumption and water consumption of the i-th decision-making unit during the evaluation period. $y_i = [y_{i1}, y_{i2}]^T$, $y_{i1}, y_{i2}$ represents the passar and water consumption of the i-th decision-making unit during the evaluation period. "$e$" represents non-Archimedes infinitesimal, generally take $10^{-6}$; "$s^-$" and "$s^+$" are slack variable; If $"θ^{-1}=1"$ and "$s^-=s^+≠0", then the decision unit is valid for DEA; If \( "θ=1" \) but "$s^-" or "$s^+" is not zero, then the decision unit is weakly valid for DEA; If "$θ"is not zero, then indicates that the decision unit is not valid for DEA, and when the $θ$ is less, the less effective it is.

In the formula (2), $e = (1,1,..,1)_{1 \times n}^T$, $θ_i^{(t)}$ indicates the efficiency of the i-th decision unit at different points in time; "$s$" represent a slack variable for efficiency, which represents the distance between the efficiency of each decision unit and the frontier of the optimal efficiency, so according to the size of "$s$", we could rank the dynamic efficiency. "$η" is the sum of components of "$s$". If "$η = 0$", then it indicates the decision unit is dynamically generating the front surface; The larger the "$η" value is, the smaller the dynamic synthesis efficiency of the decision unit in the whole time period is; the smaller the "$η" value is, the greater the dynamic integration efficiency of the decision unit is.

### 3 Case analysis

Taking the energy input for the two years from 2016 to 2017 as a sample, and selecting 12 months as the decision-making unit. The energy efficiency of the four subway lines is measured separately, and then the second line is selected as the object to analyze the energy efficiency of Wuhan rail transit. The data was provided by Wuhan Metro Operation Company, with which the thesis constructs a dynamic DEA model of Wuhan rail transit, so as to measure and evaluate the relative effectiveness of Wuhan rail transit energy utilization.

#### 3.1 Energy dynamic efficiency analysis of Wuhan rail transit Line 2

In order to dynamically analyze the energy of Wuhan rail transit, select the representative subway line 2 for dynamic analysis. Firstly, according to formula (1), use the BCC model of DEAP2.1 software to calculate the comprehensive technical efficiency, pure technology efficiency and scale efficiency of line 2, then calculate the dynamic comprehensive efficiency index "$η" of each decision unit according to equation (2) and sort, following Table 1.

**Table 1** Analysis of dynamic comprehensive efficiency index of Wuhan Metro Line 2

| Decision-making unit(month) | 2016 | 2017 |
|----------------------------|------|------|
|                            | Comprehensive technical efficiency | Pure technology efficiency | Scale efficiency | Comprehensive technical efficiency | Pure technology efficiency | Scale efficiency | Dynamic comprehensive efficiency index $η$ |
| 1                          | 0.833 | 0.895 | 0.930 (Drs) | 0.816 | 0.836 | 0.976 (Drs) | 0.361 |
| 2                          | 0.993 | 1.000 | 0.993 (Irs) | 0.911 | 1.000 | 0.911 (Irs) | 0.096 |
| 3                          | 1.000 | 1.000 | 1.000 (Con) | 1.000 | 1.000 | 1.000 (Con) | 0.120 |
| 4                          | 1.000 | 1.000 | 1.000 (Con) | 0.870 | 0.991 | 0.878 (Drs) | 0.130 |
| 5                          | 0.892 | 0.934 | 0.956 (Drs) | 0.907 | 0.975 | 0.930 (Drs) | 0.201 |
| 6                          | 0.704 | 0.901 | 0.782 (Drs) | 0.723 | 0.928 | 0.779 (Drs) | 0.573 |
| 7                          | 0.668 | 0.877 | 0.762 (Drs) | 0.619 | 0.922 | 0.672 (Drs) | 0.713 |
| 8                          | 0.540 | 0.882 | 0.612 (Drs) | 0.579 | 0.906 | 0.639 (Drs) | 0.881 |


The energy efficiency index of March and December is zero, indicating that only DEA is effective in March and December, and the efficiency is relatively stable.

In order to provide suggestions for improvement for each non-DEA effective month, the slack variable adjustment of the energy input and output of Line 2 in 2017 is obtained, and the 12-month input and output variable adjustment value and target value are shown in Table 2.

Table 2: Input and output variable adjustment values for each decision unit in 2017

| Decision-making unit (month) | 2017 |
|-----------------------------|------|
|                            | $S_x_1$ | $P_x_1$ | $S_x_2$ | $P_x_2$ | $S_y_1$ | $P_y_1$ | $S_y_2$ | $P_y_2$ |
| 1                           | -91075  | 9358147 | -11018  | 26981   | -        | 2946    | -        | 617516   |
| 2                           | -       | 9703925 | -        | 24590   | -        | 2477    | -        | 492611   |
| 3                           | -       | 8402021 | -        | 28266   | -        | 2969    | -        | 562560   |
| 4                           | -1163866 | 8402021 | -4822   | 28266   | -        | 2969    | 5862    | 562560   |
| 5                           | -600680 | 8807206 | -4199   | 27722   | -        | 2959    | -        | 585849   |
| 6                           | -3326576| 8831409 | -7015   | 27689   | -        | 2958    | -        | 587240   |
| 7                           | -4454226| 9228710 | -14961  | 27155   | -        | 2949    | -        | 610076   |
| 8                           | -5410126| 9624569 | -15685  | 26622   | -        | 2939    | -        | 632829   |
| 9                           | -4003015| 9181265 | -11435  | 27219   | -        | 2950    | -        | 607349   |
| 10                          | -1591786| 9651261 | -14436  | 26586   | 18       | 2939    | -        | 634364   |
| 11                          | -605196 | 9622323 | -2076   | 26625   | -        | 2939    | -        | 632700   |
| 12                          | -       | 9651261 | -        | 26586   | -        | 2939    | -        | 634364   |

Note: Comprehensive technical efficiency = pure technical efficiency × scale efficiency, Con, Drs respectively indicate that the energy efficiency utilization level of urban rail transit is in the range of scale benefits remain unchanged, scale benefits increasing and scale benefits decreasing.

1) According to the table 2, As far as the annual comprehensive technical efficiency is concerned, the energy efficiency of the Wuhan Metro Line 2 in the same month of the same year stay relatively stable. From the perspective of pure technical efficiency and scale efficiency, most of the decision-making units are in a state of decreasing scale efficiency, that is to say, they do not bring corresponding output with the increase of scale. Because the comprehensive technical efficiency is the product of technical efficiency and scale efficiency, the pure technical efficiency value of February, October, and November has changed from 2016 to 2017.

2) From a dynamic point of view, compared to 2016, the energy efficiency in 2017 increased in 5th, 6th, 8th, and 9th month. For example, the efficiency value in May increased from 0.892 in 2016 to 0.907 in 2017. The efficiency values for March and December are both 1, indicating that energy efficiency has been maintained for the past two months, but it is worth noting that the energy efficiency in April and November has changed from 2016 to 2017. Ranging from validity to invalidity, such as the efficiency value of 1 in April 2016, but the efficiency value in April 2017 fell to 0.870.

3) In terms of the dynamic comprehensive efficiency index, according to the dynamic DEA theory, the smaller the DEA comprehensive efficiency index is, the higher the relative efficiency is. When the comprehensive efficiency index is zero, it indicates that the decision-making unit is on the production frontier. The results show that only the dynamic comprehensive efficiency index of March and December is zero, indicating that only DEA is effective in March and December, and the efficiency value is also valid in April and April in 2016, but due to the two months of 2017’ comprehensive technical efficiency value has not reached the effective state, resulting in the final dynamic comprehensive efficiency index not reaching the effective state.
Note: “S” is the slack variable adjustment value; “P” is the target value. For example: Sx1 and Sy1 respectively indicate the slack variable adjustment values of power consumption and passenger flow; Px1 and Py1 respectively indicate the improvement target values of power consumption and passenger flow.

1. Slack variable adjustment value and target value analysis

Table 2 reflects the relationship between the adjusted value of the slack variable of each input and output variable and the target value. In order to improve the utilization efficiency of Wuhan rail transit energy, from the perspective of output, the value of the input variable should be reduced in the case of a certain demand, and the traffic passenger flow requirement can meet after adjustment. For example, the electricity consumption in June needs to be reduced by 3,326,576 degrees, and the water consumption needs to be reduced by 7015 tons.

2. Analysis of main influencing factors

By the ratio between the adjusted value and target value, the main influencing factors affecting energy efficiency can be obtained. The larger the ratio, the greater the impact on effectiveness. Taking September as an example, the ratio between the adjusted value of the input variable and the target value is 0.436 and 0.420, respectively. The proportion of electricity consumption is relatively high, indicating that electricity consumption is the main factor. Of course, the water consumption cannot be ignored.

3.3 Advices

(1) Song Miaohuan [7] shows that the adoption of low fares and government subsidy policies can encourage more residents to take subway, so the Wuhan Metro can make adjustments on the ticket price, for example, take some promotions or sale of subway monthly ticket at a fixed time of each month to increase passenger flow.

(2) Recently, the construction speed of Wuhan Metro is very fast, which indicates that the scale of Wuhan Metro is expanding, but it does not bring corresponding output. This also indicates that Wuhan Metro should make more reasonable planning, and the setting of the station should have a balance on actual passenger flow situation, such as the distance between stations in non-central urban areas can be increased. In addition, subway elevated stations and ground stations consume much less resources and construction costs than underground stations. Therefore, in the planning process of urban rail transit, Under the premise of not affecting urban planning and not destroying the urban appearance, we should consider building more elevated stations and ground stations as much as possible [8] to ensure that in the case of certain energy input, greater output will be achieved, thus optimizing the configuration of resources.

(3) From the non-effective slack variable adjustment value, it can be seen that electricity consumption is the main influencing factor of Wuhan Metro energy efficiency, which also shows that in the subway operation, Wuhan Metro should save energy as much as possible in the case of meeting basic needs. It can take some reconstruction projects, such as the ongoing renovation of energy-saving lamps in Wuhan Metro Line 2. For the vehicle's external driving lighting system, the most advanced metal halide lamps can be used for lighting, and advanced gas discharge technology is used to improve the utilization of electric energy. For the lighting of public areas inside the vehicle, some low-power energy-saving lamps can be used. On the basis of meeting passenger lighting needs, the maximum energy saving should be achieved [9]. In addition, Wuhan Metro can cooperate with contract energy management companies to meet energy-saving requirements, thereby improving energy efficiency.

4 Conclusion

(1) This thesis proposes a dynamic DEA analysis method and steps, and combines the output-based BCC evaluation model and dynamic model with the actual content of this paper. According to the actual situation and data availability of urban rail transit energy input and output indicators, select electricity consumption, water consumption as input indicators, and passenger flow and running mileage as output variables. Based on them, constructing energy efficiency effectiveness analysis and dynamic DEA model of subway.
(2) From the three aspects of technical efficiency, scale efficiency and comprehensive efficiency, the current status of energy utilization in Wuhan Metro can be seen. The overall level of energy utilization in Wuhan Metro is relatively stable. Although the energy utilization in some months has reached the technical efficiency, the scale is unreasonable. According to the slack variable and the adjustment value of the input-output variable, the construction scale of Wuhan Metro should be reasonably planned to adjust the energy consumption, so as to optimize the allocation of resources.

(3) By analyzing the adjustment values of the slack variables of various indicators in each time period, the improvement strategy should be adopted to achieve the energy efficiency effectiveness. Taking the line 2 in 2017 as an example, the results show that the indicators need to adjust except February, March and December. By analyzing the ratio between the adjusted value and the target value, it is determined that the key factor affecting the effectiveness of each non-effective decision-making unit is electricity consumption, which also indicates that the Wuhan Metro should carry out corresponding energy-saving renovation projects.

References
[1] Li Zhi, Guo Juzhen. Research on Urban Energy Efficiency Measurement Method and Evaluation[J]. Ecological Economy (Chinese Edition), 2015, 31(9): 23-27.
[2] Hu Jinli, Wang Shihchuan. Total-factor energy efficiency of regions in China [J]. Energy Policy, 2006 (17): 3206-3217.
[3] Wang Tingting. Research on China's inter-provincial energy efficiency measurement based on DEA and FDA[D]. Tsinghua University Press, 2013.
[4] Yu Guanghua. Research on energy efficiency measurement of urban rail transit based on DEA method[D]. Hebei University of Technology, 2012.
[5] Sun Wei, Wang Kunyan, Yao Xiaodong. Evaluation of Economic Benefits of Urban Public Infrastructure Based on DEA Cross Efficiency Model[J]. China Soft Science, 2015(1):172-183.
[6] Xie Aiguo, Luo Ying, Wang Yingming. Research on Theory and Method of Time Series DEA[J]. Systems Engineering and Electronics, 1999, 21(11):1-4.
[7] Song Miaohuan. Research on Beijing Rail Transit Operation Efficiency Evaluation Based on DEA[D]. Beijing Jiaotong University, 2017.
[8] Leng Wenjun. Energy Efficiency Management of Urban Rail Transit [D]. Tianjin University, 2012.
[9] Zhang Senyan. Research on Energy Conservation Management of Rail Transit Operating Enterprises [D]. Jilin University, 2016.