

# Analysis of the Operational Efficiency of Public Hospitals in Tianjin City based on a Three-Stage Data Envelopment Analysis Model

Shuai Zhao<sup>1</sup>, Lisha He<sup>1</sup>, Xiao Fu<sup>1</sup>, Weishu Ma<sup>2,\*</sup>

<sup>1</sup> Graduate School of Tianjin University of Traditional Chinese Medicine, Tianjin, China

<sup>2</sup> School of Management, Tianjin University of Traditional Chinese Medicine, Tianjin, China

\* Corresponding Author Email: maweishu@163.com

**Abstract.** The purpose is to analyze the operational efficiency of 132 public hospitals in Tianjin in 2021, providing reference for them to fully play the role of "leading institutions" and optimize resource allocation. We constructed an evaluation index system with multiple inputs, outputs, and environmental variables and utilized a three-stage DEA model to assess efficiency by removing the influence of random errors and environmental factors. The average comprehensive technical efficiency, pure technical efficiency, and scale efficiency of public hospitals were 0.865, 0.989, and 0.875, respectively. Among them, seven districts, including Heping, Hedong, and Hexi, had a comprehensive technical efficiency of 1. Among the remaining nine districts, except for Baodi, the rest showed an increasing trend in scale efficiency. Public hospitals in Tianjin City exhibit high operational efficiency, but significant variations exist among different districts, leading to uneven development. The main reason for this disparity is the presence of scale inefficiency. It is recommended to prioritize resource optimization and address the shortcomings that hinder efficiency improvement in a targeted manner. Emphasizing the "triple integration" of service capacity, efficiency, and quality in public hospitals is essential to maximize both social and economic benefits."

**Keywords:** Three-Stage Data Envelopment Analysis Model; Public Hospitals; Operational Efficiency; Tianjin.

## 1. Introduction

Public hospitals are the backbone of China's healthcare service system and play a leading role in urban medical groups [1]. In Tianjin, there is a push to shift public hospitals from a "disease-centered" approach to a "health-centered" approach [2], further promoting the development of a high-level network of public hospitals. Operational efficiency is a prerequisite for the sustained and healthy development of hospitals [3] and can also provide a direct reflection of the utilization of healthcare resources. This study focuses on 132 public hospitals in Tianjin in 2021 and analyzes their operational efficiency using a three-stage DEA model. It explores the primary reasons limiting efficiency improvement and provides rational recommendations to help public hospitals better serve as "leading institutions".

## 2. Data and Methods

### 2.1. Data Source

We obtained input and output indicators data for public hospitals in each district from the Tianjin Medical Service Evaluation and Guidance Center. Environmental variable indicators data were obtained from the "Tianjin Health and Health Statistics Yearbook" and the "Tianjin Statistical Yearbook" to use in the research.

### 2.2. Research Methods

The three-stage DEA model, as proposed by Fried et al. in 2002 [4], effectively addresses the issue of environmental variable influence in traditional DEA models. This model introduces slack variables



to mitigate the impact of external environmental factors, such as random errors and measurement errors, on managerial inefficiency. It can effectively eliminate the influence of random disturbances from external environmental factors on the values [5].

In this study, we treat the 16 districts of Tianjin as decision-making units and perform a quantitative analysis of the operational efficiency of their public hospitals. The specific calculation steps are as follows:

### **2.2.1. Initial Efficiency Measurement (First Stage):**

We use a BCC model with Input-oriented, variable returns to scale to calculate the initial efficiency of public hospital operations in each decision-making unit, along with input slack variables.

### **2.2.2. SFA Regression Model Adjustment (Second Stage):**

Based on the results from the first stage, we construct a Stochastic Frontier Analysis (SFA) regression model to eliminate the influence of environmental factors and random errors. This step involves adjusting the original inputs.

### **2.2.3. Adjusted Operational Efficiency Measurement (Third Stage):**

The input values obtained in the second stage are substituted for the input values from the first stage, while keeping the output values constant [6]. We then use the BCC model to calculate the adjusted efficiency, providing a more accurate reflection of the decision-making units' efficiency levels.

## **2.3. Indicator Selection**

Through a literature review, based on the extensive reading of numerous references [7,8,9,10], and following the principles of indicator selection, such as representativeness, feasibility, comprehensiveness, and relevance [11], as well as considering expert opinions, the following indicators were selected:

### **2.3.1. Input Indicators**

Number of hospitals, number of available beds, and the number of health technicians.

### **2.3.2. Output Indicators**

Number of outpatient and inpatient visits, and Mean length of hospital stay.

### **2.3.3. Environmental Variable Indicators**

Fiscal allocation income, per capita GDP, the proportion of tertiary hospitals, and population density.

It's worth noting that the "Mean length of hospital stay" is a low-priority indicator, and it needs to be positively transformed as follows: 1 divided by the "Mean length of hospital stay".

## **3. Results**

### **3.1. Initial Efficiency Analysis using the First Stage DEA-BCC Model**

We employed the DEA-BCC model and calculated the initial efficiency using DEAP 2.1 software. The data reveals that the average values of comprehensive technical efficiency, pure technical efficiency, and scale efficiency for the 132 public hospitals are 0.917, 0.962, and 0.954, respectively (see Table 2). Notably, nine districts, including Heping and Hedong, have a comprehensive technical efficiency value of 1, while five districts, including Hebei and Dongli, exhibit increasing returns to scale. Only Nankai and Binhai New Area show decreasing returns to scale.

### **3.2. Construction of SFA Model and Regression Analysis in the Second Stage**

The influence of external environmental variables and random errors can distort the efficiency values obtained in the first stage. Therefore, in the second stage, the Stochastic Frontier Analysis (SFA)

method is employed to avoid this interference. The difference between the input target values obtained in the first stage and the actual values, i.e., input slack variables, is taken as the dependent variable. Fiscal allocation income, per capita GDP, the proportion of tertiary hospitals, and population density variables are used as explanatory variables in the SFA regression analysis conducted with Front 4.1 software.

As shown in Table 1, the likelihood ratio tests for the three slack variables all exceed the critical values, indicating the rejection of the null hypothesis that there are no inefficiency terms. Therefore, constructing an SFA regression model is reasonable and necessary. Furthermore, their corresponding values “Y” are close to 1 and have statistical significance, suggesting that the impact of managerial inefficiency is the primary reason for the inadequate output efficiency in public hospitals [12], rather than random interference.

The positive or negative sign of the regression coefficients for environmental variables is crucial in determining the impact on the output efficiency of public hospitals. When the regression coefficient is greater than zero, it implies that an increase in environmental variables will lead to an increase in the input slack variable values, causing the original input values to deviate from the input target values [13], resulting in inadequate output efficiency. Conversely, when the regression coefficient is less than zero, it indicates a significant improvement in output efficiency.

**Table 1.** Second-stage SFA regression model results

Project	Hospital number relaxation value		Actual number of beds relaxation value		Relaxation value of the number of health technicians	
	Regression coefficient	T value	Regression coefficient	T value	Regression coefficient	T value
Constant term	-1.80E+00	-1.43E+00	-4.70E+02***	-2.30E+02	-6.54E+02***	-2.49E+02
Revenue from financial allocation	1.74E-04	9.87E-01	-3.70E-02***	-6.22E+01	-5.01E-02***	-3.22E+01
Per capita GDP	-2.73E-01	-1.19E+00	-1.83E+01***	-2.93E+01	-2.62E+01***	-1.36E+01
Third-tier public hospitals account for the proportion	-4.36E+00	-1.45E+00	-1.38E+02***	-1.34E+02	-1.80E+02***	-2.63E+02
Population density	-3.74E-01	-4.60E-01	6.99E+00**	1.94E+00	4.19E+00	5.21E-01
$\sigma^2$	3.38E+00		1.83E+05		3.68E+05	
$\gamma$	0.75		1.000		1.00	
Logarithmic likelihood function	2.90E+06		5.97E+06		7.75E+07	
LR unilateral test	3.29E-02		6.60E+00*		7.05E+00*	

### 3.3. Analysis of Adjusted Operational Efficiency in the Third Stage

By separating the managerial inefficiency terms from the second stage, adjusted input values were obtained and used in the DEA-BCC model to calculate the final efficiency values. The data shows that the comprehensive technical efficiency and scale efficiency of public hospitals in Tianjin decreased from 0.917 and 0.954 to 0.865 and 0.875, respectively. On the other hand, pure technical efficiency increased from 0.962 to 0.989. This indicates that, without considering the influence of external environmental factors, the operational efficiency of public hospitals in Tianjin is artificially high, and low scale efficiency is the primary obstacle to improving operational efficiency. After adjustment, seven districts had a comprehensive technical efficiency of 1, accounting for 43.75%. Among them, 87.5% of the regions had a pure technical efficiency of 1, and 56.25% of the regions

had a scale efficiency of 1. Only Baodi District showed decreasing returns to scale, as shown in Table 2.

**Table 2.** Comparison of operating efficiency of DEA public hospitals in three phases before and after adjustment

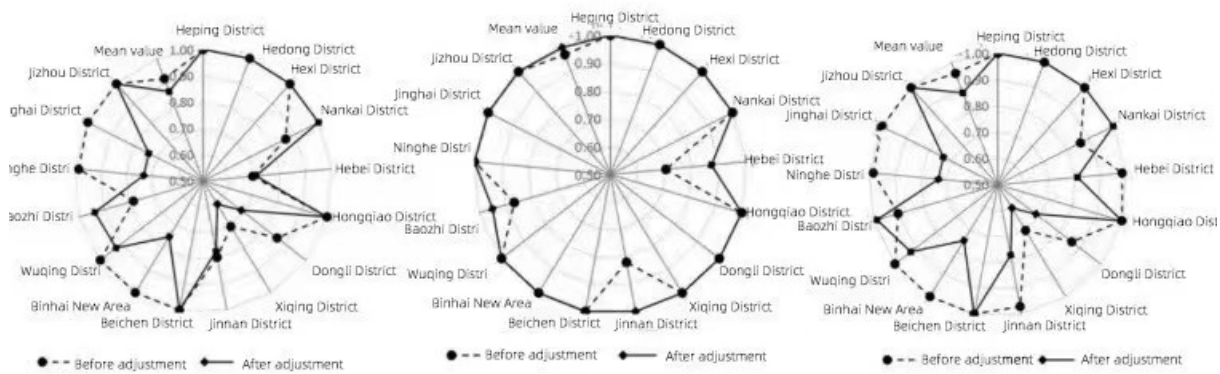
Region	Before adjustment				After adjustment			
	Comprehensive technical efficiency	Pure technical efficiency	Scale efficiency	Scale reward	Comprehensive technical efficiency	Pure technical efficiency	Scale efficiency	Scale reward
Mean value	0.917	0.962	0.954		0.865	0.989	0.875	
Heping District	1.000	1.000	1.000	—	1.000	1.000	1.000	—
Hedong District	1.000	1.000	1.000	—	1.000	1.000	1.000	—
Hexi District	1.000	1.000	1.000	—	1.000	1.000	1.000	—
Nankai District	0.858	1.000	0.858	drs	1.000	1.000	1.000	—
Hebei District	0.693	0.704	0.984	irs	0.706	0.872	0.810	irs
Hongqiao District	1.000	1.000	1.000	—	1.000	1.000	1.000	—
Dongli District	0.860	1.000	0.860	irs	0.685	1.000	0.685	irs
Xiqing District	0.704	1.000	0.704	irs	0.604	1.000	0.604	irs
Jinnan District	0.796	0.820	0.971	irs	0.772	1.000	0.772	irs
Beichen District	1.000	1.000	1.000	—	1.000	1.000	1.000	—
Binhai New Area	1.000	1.000	1.000	—	0.750	1.000	0.750	irs
Wuqing District	1.000	1.000	1.000	—	0.923	1.000	0.923	irs
Baodi District	0.781	0.866	0.902	drs	0.937	0.949	0.987	drs
Ninghe District	0.985	1.000	0.985	irs	0.731	1.000	0.731	irs
Jinghai District	1.000	1.000	1.000	—	0.736	1.000	0.736	irs
Jizhou District	1.000	1.000	1.000	—	1.000	1.000	1.000	—

Comprehensive technical efficiency is determined by both pure technical efficiency and scale efficiency. Pure technical efficiency reflects the decision-making unit's management and technological level, while scale efficiency reflects the level of resource allocation [14]. Looking at the comprehensive analysis in Figure 1 and Table 2, it is evident that in terms of comprehensive technical efficiency, districts such as Heping, Hedong, Hexi, Hongqiao, Beichen, and Jizhou consistently maintained an efficiency of 1. After adjustment, Nankai achieved an efficiency of 1, indicating that these districts' public hospital resources are reasonably allocated, and their medical technology and management levels are relatively high. WUqing and Baodi exhibit efficiencies higher than the city average, at 0.923 and 0.937, respectively. However, seven districts demonstrate efficiencies lower than the city average, among which Jinghai, Ninghe, and Binhai New Area show the most significant decrease in efficiency. They dropped from 1.000, 0.985, and 1.000 to 0.736, 0.731, and 0.750, respectively, indicating a substantial influence of external environmental factors on their efficiency. Xiqing (0.604) and Dongli (0.685) consistently remain at the “bottom,” suggesting that issues related to unreasonable resource allocation and utilization in their public hospitals are most prominent.

In terms of pure technical efficiency, all districts saw an improvement in pure technical efficiency after adjustment. In the first stage, the influence of external environmental and random factors led to

lower actual efficiency values. This suggests that the public hospitals in Tianjin have relatively high levels of management and technological expertise.

Regarding scale efficiency, 62.5% of districts still have efficiency values below 1, indicating that the resource allocation in their public hospitals is not rational. Among them, Baodi has the highest scale efficiency at 0.987, while Xiqing has the lowest at 0.604, showing a significant difference between districts.



**Figure 1.** Comparison chart of comprehensive technical efficiency (left), pure technical efficiency (middle), and scale efficiency (right) before and after adjustment

## 4. Conclusion

### 4.1. Public Hospitals in Tianjin City Exhibit High Operational Efficiency with Room for Improvement

Across the entire city, seven districts have public hospital operational efficiency in a DEA-effective state. With more than 87.5% of districts achieving a pure technical efficiency of 1 and an overall mean of 0.989, it is evident that the management capabilities and technological proficiency of public hospitals are maturing. However, the comprehensive technical efficiency and scale efficiency stand at 0.865 and 0.875, respectively, which suggests that there is still room for improvement when compared to the figures from Guangdong Province in 2019 (0.977, 0.989, and 0.988) [6]. the recommendations are as follows:

#### 4.1.1. At the Management Level, It is Advisable to Promote the Cross-Development of Public Hospitals of Different Types, Levels, and Specialties

Reasonable allocation of regional healthcare resources is essential to maximize efficiency and effectiveness with limited resources.

#### 4.1.2. At the Hospital Level, the First Step Should be to Assess the Hospital's Own Positioning.

Considering the strengths of different departments in terms of diagnosis and treatment, as well as the development of medical technology, can help in the rational allocation of internal hospital resources [15].

#### 4.1.3. Focus on Establishing an Integrated High-Quality Service System and Ensure the Seamless Implementation of Assessment and Evaluation Systems, Such as the Evaluation of Tertiary Hospitals and the Performance Assessment of Public Hospitals

These systems should serve as effective tools for improving operational efficiency in public hospitals. This approach aligns with the goal of advancing the 'triple integration' of public hospital service capacity, efficiency, and quality [16].

## **4.2. Uneven Public Hospital Operational Efficiency among Districts with Significant Spatial Disparities**

Public hospitals with a comprehensive technical efficiency of 1 are primarily concentrated in the central urban areas, with fewer such hospitals in other regions. Among the nine districts that have not reached a DEA-effective state, Baodi has the highest comprehensive technical efficiency (0.937), approximately 1.6 times that of Xiqing (0.604). The reason behind this difference lies in the fact that while Xiqing has a pure technical efficiency of 1, its scale efficiency (0.604) is the lowest in the city. In contrast, Baodi maintains relatively stable efficiency scores across all three indicators (0.937, 0.949, and 0.987). Similar development patterns can be observed in Dongli, Jinnan, and six other districts, indicating that inefficient resource allocation in public hospitals directly leads to operational efficiency imbalances. The recommendations are as follows:

### **4.2.1. Strengthen the Current Level of Healthcare Management and Technical Achievements.**

Accelerate innovation in institutional mechanisms, effectively manage resources, and introduce new technologies and equipment [17].

### **4.2.2. Focus on Optimizing Resource Allocation as a Core Objective.**

Employ policies, financial support, and other means to promote rational resource allocation in various districts.

### **4.2.3. Continue to Enhance 'Internet + Healthcare' Technologies to Enable Remote Diagnosis and Treatment, Improving the Level of Medical Services in Areas with Lower Efficiency**

Coordinate and synergize development efforts [18].

## **4.3. Strengthen the Precision Management of Environmental Variables for a Transformational Leap:**

Regression analysis reveals that fiscal allocation, per capita GDP, and the proportion of tertiary public hospitals exhibit negative regression coefficients for the number of beds and healthcare personnel, all significant at the 1% level. This suggests that an increase in these environmental variables contributes to reducing slack in beds and healthcare personnel, thereby promoting improved operational efficiency. On the other hand, population density exhibits a positive regression coefficient for the number of beds, significant at the 5% level. This implies that in central urban areas with relatively higher economic development levels, population density growth might lead to an indiscriminate expansion of bed numbers, resulting in decreased operational efficiency. The recommendations are as follows:

### **4.3.1. Continuously Optimize The Internal and External Environment to Create Favorable Conditions for Deepening the Reform of Public Hospitals.**

This optimization should be targeted to address the 'weak points' in the development of public hospitals in areas such as Xiqing, Dongli, and Hebei. Implement a precision management approach [19] to achieve the development goal of “enhancing efficiency.”

### **4.3.2. Develop a Flexible and Tailored Development System That Guides Regions with Lower Operational Efficiency in Public Hospitals.**

This approach should adapt to changing external conditions. While increasing financial, physical, and human resources, continuously enhance management capabilities and, where appropriate, expand the scale of operations [20]. This should lead to maximizing social and economic benefits, effectively utilizing public hospitals as regional “leaders.”

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