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COVID-19: Evaluation of S&T Innovation Efficiency of 14 Prefecture-level Cities in Hunan Province under the Background of Climate Change-Based on Dynamic Network DEA with a New Framework

Journal of Electrical Systems

Abstract: - With the urban development entering a new stage, science and technology innovation (S&T innovation) is becoming more and more important for urban development. Nowadays,the influence of global climate change on cities is increasing,and different cities have different climate changes,which have different degrees of influence on scientific and technological innovation in different cities.Urban scientific and technological strength plays an important role in urban economic growth, greatly promotes urban economic growth and industrial upgrading, and expedites the development of urban comprehensive competitiveness. At present, it is necessary to use dynamic network DEA method to study the efficiency of scientific and technological innovation of 14 prefecture-level cities in Hunan Province. Therefore, in this paper, the dynamic network DEA with a new framework was adopted to evaluate and study the S&T innovation efficiency of 14 prefecture-level cities in Hunan Province with the panel data from 2016 to 2021.The data of 2019 to 2021 include the data during the covid-19.dynamic network DEA is a new research framework that combines two-stage network DEA and Malmquist Index Approach to analyze the index of each prefecture-level city. Relevant suggestions were put forward according to the index. The results show that the tfp (total factor productivity) index values of S&T innovation in 14 prefecture-level cities of Hunan Province from 2016 to 2021 showed a gradual improvement trend; technological progress is an important factor affecting the tfp of S&T innovation; and there are regional differences in the tfp of S&T innovation in different cities.The suggestions put forward in this paper are as follows: policy support for scientific and technological innovation, scientific management, and strengthening the scientific and technological system of prefecture-level cities.

Keywords: *S&T innovation; dynamic network DEA; prefecture-level cities in Hunan Province;climate change;covid-19*

I. INTRODUCTION

The state has further promoted the innovation-driven development strategy and the CCP committee and government of Hunan Province have implemented the strategy "innovation-led development, opening up and rise", to promote the development driven by S&T innovation and take S&T innovation as the main force driving development. To develop and improve innovation capacity, provinces and cities need to continuously input innovative resources, and pay attention to the conversion rate of resource input and actual output. This is of great significance for the healthy and sustainable development of a province and even a country's economy. Therefore, the dynamic network DEA was adopted in this paper to evaluate and study the S&T innovation efficiency of 14 prefecture-level cities in Hunan Province from 2016 to 2021, and to analyze its dynamic changes and reasons. This paper also provides a scientific and valid basis for relevant government departments to further improve S&T innovation efficiency, optimize resource allocation and formulate more scientific and reasonable innovation

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policies and suggestions, which is of great significance for predicting their future development trend and future development..

Kao[4] (2009) established a relational two-stage DEA model, and Charnes, Cooper, and Rhodes[1] (1978) proposed an input-oriented CCR model. Simar and Wilson[3] (1998) proposed the bootstrap DEA analysis method, and Fare et al.[2] (1994) proposed the DEA-Malmquist model. *Efficiency Analysis of S&T Innovation in Prefecture-level Cities in Hunan Province-- Based on DEA-Malmquist Index* by Deng and Zhang[5] (2021)suggested: (1) During the study period, the S&T innovation efficiency of Hunan Province was on the rise, but the efficiency value was low, and large regional differences still existed; (2) Pure technical efficiency is the main factor hindering the improvement of input-output efficiency; (3) In terms of regional comparison, the total factor productivity of S&T innovation in Changde City, Zhangjiajie and Yongzhou was lower, while that in Xiangxi Prefecture, Yueyang and Zhuzhou was higher. For the selection of indicators, this paper refers to the research results from the *Evaluation and Comparison of Input Redundancy for Science-Technological Innovation Efficiency about Chinese 31 Provinces* by Guo and Zhang[8] (2018): (1) The number of provinces with full efficiency in the study period showed an increasing trend, but the total number was still far less than half; (2) In the past five years, the S&T innovation efficiency of provinces and cities has been improved based on technological progress; (3) Only eight provinces are zero-redundancy areas. At present, the state still needs to further reform the science and technology management policy and guide the optimal allocation of regional science and technology resources; (4) All provinces and cities should implement S&T innovation policies with local characteristics based on the redundancy of local science and technology resources and resource endowment. *Evaluation of S&T Innovation Efficiency of Guangdong-Hong Kong-Macao Greater Bay Area based on DEA-Malmquist Index* by Zhang et al.[6] (2021) suggested: (1) The productivity of S&T innovation in Guangdong-Hong Kong-Macao Greater Bay Area has steadily increased; (2) Technological progress is the key factor to promote the productivity of S&T innovation; (3) There are differences in the change of S&T innovation efficiency in different cities, and scale efficiency plays an obvious hindrance to the improvement of technical efficiency, thus inhibiting the level of S&T innovation efficiency. The results from *A Study of Innovation Efficiency Evaluation and Promotion Path of Regional Patent Intensive Industries by Taking Zhejiang Province as an Example* by Wang, Wang, and Yu[10] (2017) showed that the innovation efficiency of regional patent-intensive industries was better than that of non-patent-intensive industries, but not all aspects of DEA were effective, and resource input and output did not match in physical output and value output, and input redundancy was serious. Liu[11] (2017) conducted a dynamic evaluation of the innovation efficiency of Guangdong's regional innovation system based on DEA-Malmquist Index Approach, and the results showed that the innovation efficiency of Guangdong's regional innovation system showed a gradual improvement trend from 2009 to 2013, but technology recession became one of the key factors hindering the growth of innovation efficiency. The regional innovation system of Guangdong Province has not reached the optimal production scale, and the input of innovation resources was still insufficient. The change trend of innovation efficiency of Guangdong's regional innovation system was highly consistent with that of scale efficiency, while the change of pure technology efficiency and scale efficiency was opposite to that of technology change. In the model construction and empirical research, this paper refers to the *New Network DEA Model and Its Application in Bank Efficiency Evaluation* by Liu[7] (2020) and the *Dynamic Empirical Analysis of Total Factor Productivity of S&T Innovation in Fujian: Based on DEA-Malmquist Index Model and Urban Panel Data* by Li[9] (2018).

Based on the above literature, the innovation and difference of this paper is that a new research method (dynamic network DEA) was adopted and two-stage new network DEA was combined with Malmquist index to study the evaluation of S&T innovation efficiency of 14 prefecture-level cities in Hunan Province. In addition, few scholars have studied the evaluation of S&T innovation efficiency of 14 prefecture-level cities in Hunan Province.

II. MODEL CONSTRUCTION

To study the dynamic S&T innovation efficiency of 14 prefecture-level cities of Hunan Province, this paper used dynamic network DEA to study the dynamic change of S&T innovation efficiency of 14 prefecture-level cities of Hunan Province and the reasons.

A. Two-stage new network DEA

There are two main types of two-stage network DEA. The first type is the output of only intermediate variables in the first stage, and the input of only intermediate variables in the second stage.The second type is more common, the first stage only has the output of intermediate variables, while the se cond stage has both the input of intermediate variables and additional inputs, and the output of the first stage is o ne of the inputs of intermediate variables in the second stage[13].This paper is based on the second type of two-stage network DEA.

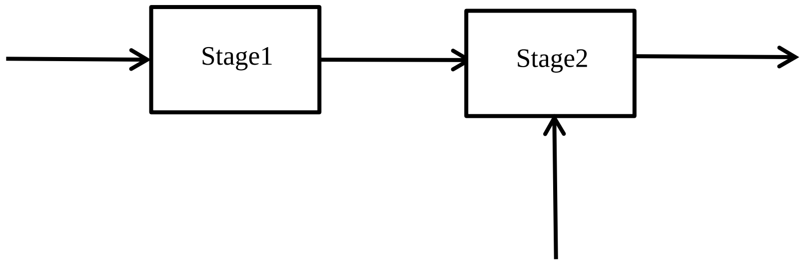

Figure 1 The Second Type of Two-stage New Network DEA

At present, the two-stage DEA method can be divided into four types, namely, the first type is an independent two-stage DEA, which applies the standard DEA method to two different stages independently; the second type is a connected two-stage method, which is used to calculate the overall efficiency and considers the interaction; The third is a relati onal two-stage DEA method, which constructs the relationship between the whole efficiency and the efficiency of each su b-process. The fourth model is a game theory model. In this paper, the third relational two-stage DEA method is used to construct the overall efficiency and the efficiency of each sub-process.The relationship between rates[12].

Assuming that in $DMU_p(p \in \{1, \cdots, n\})$, x_{ip},z_{kp} are respectively the i-th input $(i = 1, \cdots, m)$ in the first subprocess and k-th output $(k = 1, \cdots, q)$, and z_{kp}, y_{rp} are respectively the k-th input $(k = 1, \cdots, q)$ and the r-th output r=$(r = 1, \cdots, s)$ in the second subprocess, the following models (1) and (2) are used to measure the efficiency of the two subprocesses *respectively*.

$$\theta_{box}^{1} = \min \frac{2\sum_{i=1}^{m} v_i x_{ip}}{\sum_{i=1}^{m} v_i x_{ip} + \sum_{k=1}^{q} w_{kr} z_{kp}}, \sum_{i=1}^{m} v_i x_{ij} - \sum_{k=1}^{q} w_k z_{kj} \geq 0, j = 1, \cdots, n, v_i, w_k \geq 0, \forall i, k, \quad (1)$$

$$\theta_{box}^{2}=\min \frac{2\sum_{i=1}^{q} c_k z_{kp}}{\sum_{k=1}^{m} c_k z_{kp}+\sum_{r=1}^{s} u_r y_{rp}}, \sum_{k=1}^{q} c_k z_{kj}-\sum_{r=1}^{s} u_r y_{rj} \geq 0, j=1,\cdots,n, c_k, y_r \geq 0, \forall k, r. \quad (2)$$

Models (1) and (2) are two independent processes and do not take into account the particularity of the intermediate variable z_{kp}, which means that z_{kp} is both the output in the first subprocess and the input in the second subprocess. z_{kp}, as the output in the first subprocess, is expected to the biggest output, but z_{kp}, as the input in the second subprocess, is expected to be the smallest input. Therefore, Kao[4] (2009) considered the relationship between DMU internal processes and pointed out that when calculating system efficiency, the weight of a certain element in the system is always the same, whether it represents input or output or which subprocess it is used for. On this basis, this paper builds the following model:

$$\theta_{p}^{*}=\min \frac{2\sum_{i=1}^{m} v_i x_{ip}+2\sum_{k=1}^{q} w_k z_{kp}}{\sum_{i=1}^{m} v_i x_{ip}+2\sum_{k=1}^{q} w_k z_{kp}+\sum_{r=1}^{s} u_r y_{rp}}, s.t. \sum_{i=1}^{m} v_i x_{ij}-\sum_{k=1}^{q} w_k z_{kj} \geq 0, j=1,\cdots,n, \quad (3)$$

$$\sum_{k=1}^{q} w_k z_{kj}-\sum_{r=1}^{s} u_r y_{rj} \geq 0, j=1,\cdots,n, v_i, u_r, w_k \geq 0, \forall i, r, k$$

By Charnes-Cooper linear transformation, fraction model (3) can be transformed into the following linear model:

$$\theta_{p}^{*}=\min 2\sum_{i=1}^{m} v_i x_{ip}+2\sum_{k=1}^{q} w_k z_{kp}, s.t. \sum_{i=1}^{m} v_i x_{ip}+2\sum_{k=1}^{q} w_k z_{kp}+\sum_{r=1}^{s} u_r y_{rp}=1,$$

$$\sum_{i=1}^{m} v_i x_{ij}-\sum_{k=1}^{q} w_k z_{kj} \geq 0, j=1,\cdots,n, \sum_{k=1}^{q} w_k z_{kj}-\sum_{r=1}^{s} u_r y_{rj} \geq 0, j=1,\cdots,n, \quad (4)$$

$$v_i, u_r, w_k \geq 0, \forall i, r, k.$$

Theorem 1 Assuming that θ_p^* is the optimal solution of model (3), $1 \leq \theta_p^* \leq 2$ can be obtained.

It proves that according to the constraints in model (3),

$$\sum_{i=1}^{m} v_i x_{ij} \geq \sum_{k=1}^{q} w_k z_{kj}, \sum_{k=1}^{q} w_k z_{kj} \geq \sum_{r=1}^{s} u_r y_{rj},$$

so , and $\sum_{i=1}^{m} v_i x_{ip} \geq \sum_{r=1}^{s} u_r y_{rp}$

$$\theta_{p}^{*}-1=\frac{\sum_{i=1}^{m} v_i x_{ip}-\sum_{r=1}^{s} u_r y_{rp}}{\sum_{i=1}^{m} v_i x_{ip}+2\sum_{k=1}^{q} w_k z_{kp}+\sum_{r=1}^{s} u_r y_{rp}} \geq 0, 2-\theta_{p}^{*}=\frac{2\sum_{k=1}^{q} w_k z_{kp}+1\sum_{r=1}^{s} u_r y_{rp}}{\sum_{i=1}^{m} v_i x_{ip}+2\sum_{k=1}^{q} w_k z_{kp}+\sum_{r=1}^{s} u_r y_{rp}} \geq 0$$

therefore, $1 \leq \theta_p^* \leq 2$ is proven.

Definition 1: Assuming that $\left(v_{1p}^*, \cdots, v_{mp}^*, u_{1p}^*, \cdots, u_{sp}^*, w_{1p}^*, \cdots, w_{qp}^*\right)$ is an optimal solution for model (3), the efficiencies of DMU$_p$ and its two subprocesses are:

$$E_p^s = 2 - \theta_p^* = \frac{2\sum_{k=1}^{q} w_k^* z_{kp} + 2\sum_{r=1}^{s} u_r^* y_{rp}}{\sum_{i=1}^{m} v_i^* x_{ip} + 2\sum_{k=1}^{q} w_k z_{kp} + \sum_{r=1}^{s} u_r^* y_{rp}}, (5)$$

$$E_p^{1*} = \frac{2\sum_{k=1}^{q} w_k^* z_{kp}}{\sum_{i=1}^{m} v_i^* x_{ip} + \sum_{k=1}^{q} w_k^* z_{kp}}, (6)$$

$$E_p^{2*} = \frac{2\sum_{k=1}^{q} u_r^* y_{rp}}{\sum_{k=1}^{q} w_k^* z_{kp} + \sum_{k=1}^{q} u_r^* y_{rp}}, (7)$$

Definition 2: Assuming that $\left(v_{1p}^*, \cdots, v_{mp}^*, u_{1p}^*, \cdots, u_{sp}^*, w_{1p}^*, \cdots, w_{qp}^*\right)$ is an optimal solution for model (3), then the overall DMU$_p$ efficiency E_p^s is equal to the weighted average sum of the efficiencies of the two subprocesses.

Assuming that ω_1^* and ω_2^* are the weights of the first and second subprocesses, respectively, where:

$$\omega_1^* = \frac{\sum_{i=1}^{m} v_i^* x_{ip} + \sum_{k=1}^{q} w_k^* z_{kp}}{\sum_{i=1}^{m} v_i^* x_{ip} + 2\sum_{k=1}^{q} w_k^* z_{kp} + \sum_{r=1}^{s} u_r^* y_{rp}}. (8)$$

and $\omega_1^* + \omega_2^* = 1$, so $\omega_2^* = 1 - \omega_1^*$,

$$\omega_2^* = \frac{\sum_{k=1}^{q} w_k^* z_{kp} + \sum_{r=1}^{s} u_r^* y_{rp}}{\sum_{i=1}^{m} v_i^* x_{ip} + 2\sum_{k=1}^{q} w_k^* z_{kp} + \sum_{r=1}^{s} u_r^* y_{rp}}$$

It can be known from Definition 2, $\omega_1^* E_p^{1*} + \omega_2^* E_p^{2*} = E_p^s$.

B. Malmquist index

Data envelopment analysis (DEA) model (also known as input oriented CCR model), was first proposed by Charnes, Cooper, and Rhodes[1] (1978) under the assumption of a constant returns to scale production technology. However, due to the limited observed samples (DMU), it is difficult to avoid the influence of sample sensitivity and extreme values in the measured efficiency value results. Simar and Wilson[3] (1998) proposed bootstrap DEA analysis to avoid this problem. Based on this, DEA model can only study and compare the efficiency values of different DMU in a certain period, but cannot study the efficiency values of different periods.

Fare et al.[2] (1994) combined Malmquist index theory with DEA for the first time and proposed the DEA-Malmquist model. The dynamic DEA-Malmquist index evaluates the efficiency value of each unit in different periods, which solves the defect that the DEA model cannot study the efficiency value in different periods. Assuming that (x^t, y^t) represents the input and output of the t period, (x^{t+1}, y^{t+1}) represents the input and output of the t+1 period, $D_c^t(x^t, y^t)$ and $D_c^{t+1}(x^{t+1}, y^{t+1})$ are the output distance function under the technical conditions of the corresponding period, where the subscript c indicates the constant returns to scale, the Malmquist index can be expressed by the following formula:

$$tfp=M^{t+1}(x^{t+1}, y^{t+1}, x^t, y^t)=\sqrt{\left[\frac{D_c^t(x^{t+1},y^{t+1})}{D_c^t(x^t,y^t)} \times \frac{D_c^{t+1}(x^{t+1},y^{t+1})}{D_c^{t+1}(x^t,y^t)}\right]} \quad (1)$$

When $M^{t+1}(x^{t+1}, y^{t+1}, x^t, y^t)>1$, it means that the total factor productivity improves. When $M^{t+1}(x^{t+1}, y^{t+1}, x^t, y^t)<1$, it means that the total factor productivity declines. When $M^{t+1}(x^{t+1}, y^{t+1}, x^t, y^t)=1$, it means that the total factor productivity is unchanged. When the value of each change index is greater than 1, it indicates improvement; when the value of each change index =1, it indicates unchanged; when the value of each change index is less than 1, it indicates a decline. Further, under the assumption of constant returns to scale, the Malmquist index can be decomposed into technical efficiency change index (Effch) and technological progress index (Tech), and the specific formula is shown below:

$$Effch=\frac{D_c^{t+1}(x^{t+1},y^{t+1})}{D_c^t(x^t,y^t)} \quad (2)$$

$$Tech=\sqrt{\left[\frac{D_c^t(x^{t+1},y^{t+1})}{D_c^{t+1}(x^{t+1},y^{t+1})} \times \frac{D_c^t(x^t,y^t)}{D_c^{t+1}(x^t,y^t)}\right]} \quad (3)$$

Where $tfp=M^{t+1}(x^{t+1}, y^{t+1}, x^t, y^t)=Effch\times Tech$.

When the constant returns to scale are variable, the technical efficiency change index can be further decomposed into pure technical efficiency index (pech) and scale efficiency index (sech). Its expression is: $pech=\frac{D_v^{t+1}(x^{t+1},y^{t+1})}{D_v^{t+1}(x^t,y^t)}$ (4) $sech=\sqrt{\left[\frac{D_v^{t+1}(x^{t+1},y^{t+1})/D_v^{t+1}(x^{t+1},y^{t+1})}{D_v^t(x^t,y^t)/D_v^t(x^t,y^t)} \times \frac{D_v^{t+1}(x^{t+1},y^{t+1})/D_c^{t+1}(x^{t+1},y^{t+1})}{D_v^t(x^t,y^t)/D_c^t(x^t,y^t)}\right]}$ (5)

Where, $D_v^{t+1}(x^{t+1}, y^{t+1})$ represents the output distance function based on the technical conditions of the t+1 phase when returns to scale are variable, and subscript v represents variable returns to scale. The technical efficiency change index can be expressed as: effch=pech×sech. Therefore, the calculation formula of total factor productivity, i.e. the S&T innovation efficiency, is as follows:

$$tfp=Effch\times Tech=pech\times sech\times tech \quad (5)$$

C. Selection of index system

In this paper, the index of S&T innovation in 14 prefecture-level cities of Hunan Province is divided into two categories: input index and output index. With reference to the research conducted by Guo and Zhang[8] and Zhang et al.[6], in the first stage, the input index of this paper is selected from the human and financial resources, which are respectively the number of R&D personnel (people) of industrial enterprises above designated size, and internal expenditure of industrial enterprises above designated size (RMB ten thousand); the output index is the number of patent applications (applications) of industrial enterprises above designated size. By referring to the result that output index reduces energy consumption and new product output value in Liu Mingguang's research on the dynamic evaluation of innovation efficiency of Guangdong's regional innovation system based on DEA-Malmquist Index Approach, namely, based on the previous study, this paper, the reciprocal of comprehensive energy consumption of industrial enterprises above designated size (1/10,000 tons) and the output index of the first stage, the number of patent applications of industrial enterprises above designated size (cases) are used as the input index of the second stage. According to the findings of Wang[10] and Wang[10], the output index of the second stage of this paper is the sales income of new products of industrial enterprises above designated size (RMB ten thousand). In this paper, the inverse comprehensive energy consumption of industrial enterprises above designated size is taken as the input condition to produce new products. Comprehensive energy consumption of industrial enterprises above designated size should be a reverse index to reflect scientific and technological innovation, and in order to make the index positively reflect the S&T innovation efficiency, the author adopted the inverse comprehensive energy consumption of industrial enterprises above designated size as the input index of the second stage in this paper. In summary, the input index of the total stage is the number of R&D personnel (people) of industrial enterprises above designated size and the internal expenditure of industrial enterprises above designated size (RMB ten thousand); the output index is the sales income of new products of industrial enterprises above designated size (RMB ten thousand).

Table 1 Input-output Index of S&T Innovation Efficiency

Index type	Index	Unit
Input1	Number of R&D personnel in industrial enterprises above designated size	people
Input1	Internal R&D expenditure of industrial enterprises above designated size	RMB ten thousand
Intermediate	Number of patent applications by industrial enterprises above designated size	cases
Input2	Inverse comprehensive energy consumption of industrial enterprises above designated size	1/10,000 tons
Output2	Sales revenue of new products of industrial enterprises above designated size	RMB ten thousand

Input1 is the input of the first node; output1 is the output of the first node; Intermediate is the intermediate variable; Input2 is the input of the second node; Output2 is the output of the second node.

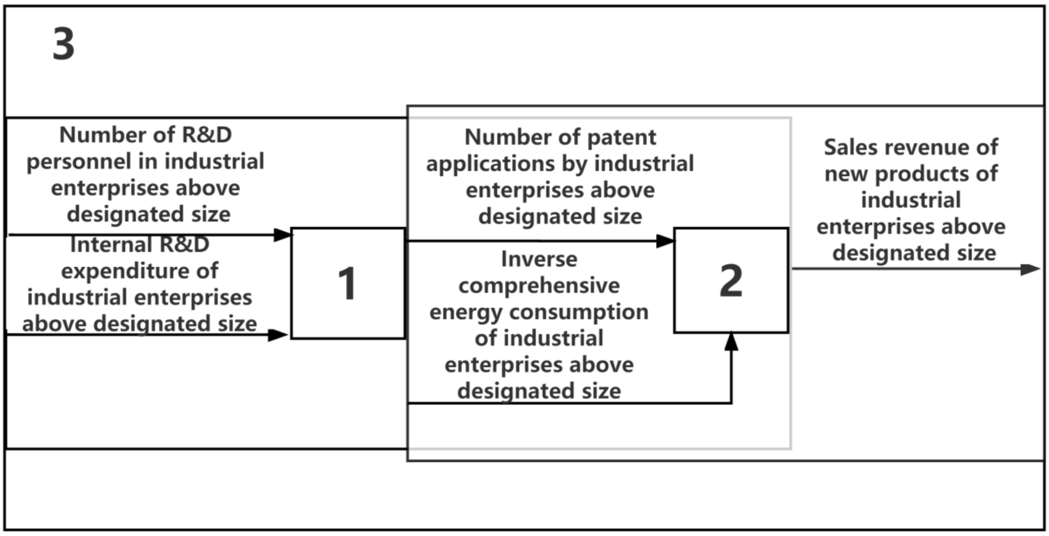

Figure 2 Research Index System of S&T Innovation Dynamics in 14 Prefecture-level Cities in Hunan Province

In this paper, Figure 2 is disassembled into Figure 2-1, Figure 2-2 and Figure 2-3, and reference is made to the research findings of Guo Shufen[8] and Zhang Jun[8], Zhang et al.[6]. In Figure 3, the input index in the first stage is the number of R&D personnel (people) of industrial enterprises above designated size and the internal expenditure of industrial enterprises above designated size (RMB ten thousand) in this paper; the output index is the number of patent applications (applications) of industrial enterprises above designated size. In Figure 4, the input index in the second stage is the number of patent applications of industrial enterprises above designated size and the inverse comprehensive energy consumption of industrial enterprises above designated size; the output index is the sales revenue of new products of industrial enterprises above designated size. In Figure 5, the investment index in the third stage, that is, the overall network stage, is the number of R&D personnel of industrial enterprises above designated size (people), and the internal expenditure of industrial enterprises above designated size (RMB ten thousand); the output indicator is the sales revenue of new products of industrial enterprises above designated size. The DEA-Malmquist Index Approach was used in all three network stages to understand which stage caused the performance of the overall efficiency value, and to analyze the efficiency difference of each performance value after the efficiency decomposition of the stage.

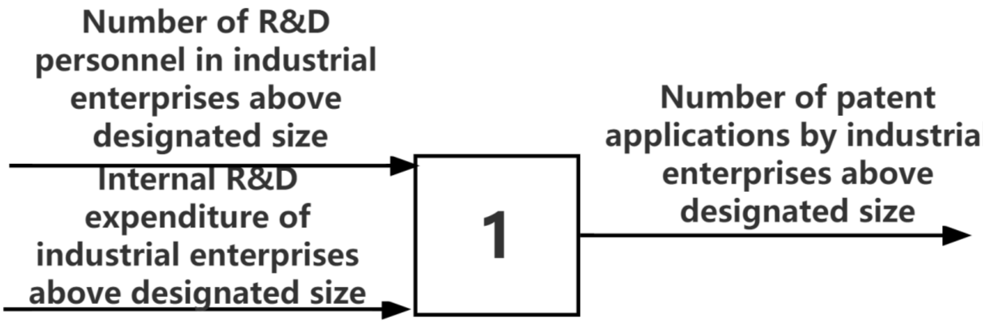

Figure 2-1 First-stage Index System of Research on S&T Innovation Dynamic Network in 14 Prefecture-level Cities in Hunan Province based on DEA

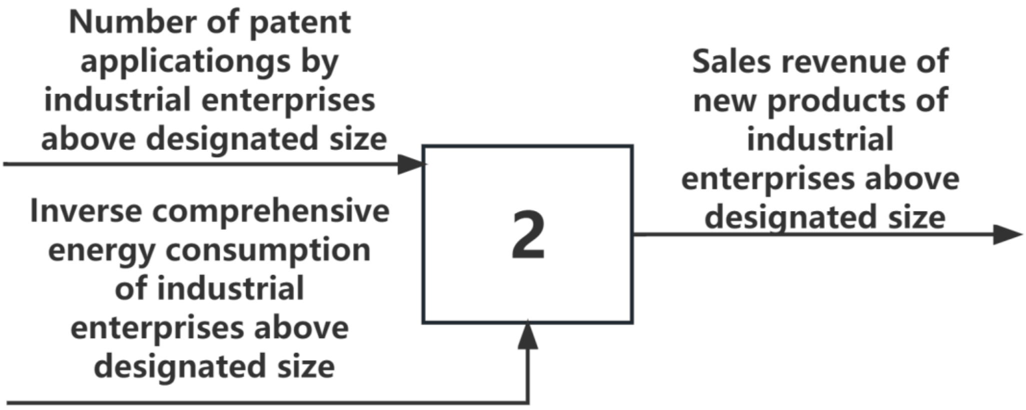

Figure 2-2 Second-stage Index System of Research on S&T Innovation Dynamic Network in 14 Prefecture-level Cities in Hunan Province based on DEA

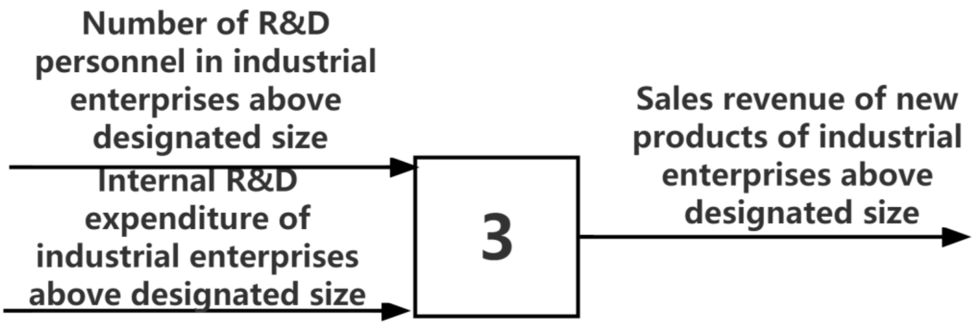

Figure 2-3 Overall Network Stage Index System of Research on S&T Innovation Dynamic Network in 14 Prefecture-level Cities in Hunan Province based on DEA

III. EMPIRICAL RESEARCH

The empirical analysis data in this paper are mainly from the *Statistical Yearbook of Hunan Province (2016-2021)*. Due to the limited data, the years from 2016 to 2021 were selected as the research period, and 14 prefecture-level cities in Hunan Province were selected as the research subject. The pure technical efficiency, scale efficiency, technological progress and comprehensive efficiency indexes of S&T innovation in prefecture-level cities and Xiangxi Prefecture were studied and analyzed, and relevant suggestions were provided based on the analysis results. By using MaxDEA software, the DEA-Malmquist index (tfp) was calculated for 14 prefecture-level cities in Hunan Province's regional S&T innovation system, and it was decomposed into pure technical efficiency (pech), scale efficiency (sech), technological progress (tech), and technical efficiency. The data analysis of the total stage is shown in Table 2.

As can be seen from Table 2, the comprehensive innovation efficiency (tfp) from 2016 to 2021 showed an increase rend, and the comprehensive innovation efficiency (tfp) value from 2019 to 2021 is >1. Although the total innovation efficiency improved, from 2019 to 2021, the technical efficiency (effch) and pure technical efficiency (pech) declined, while the scale efficiency improved, so the decline in technical efficiency was mainly caused by the decline in pure technical efficiency. Due to the COVID-19 outbreak in 2019-2021, the progress of pure technical efficiency was delayed and lagged behind. Compared with 2016-2017, pure technical efficiency (pech) declined significantly in 2017-2018. This in turn affected the comprehensive innovation efficiency (tfp) and technical efficiency (effch) values for 2017-2018. On the whole, the average of each index improved.

Table 2 Average Malmquist Index and Decomposition of S&T Innovation Efficiency of 14 Prefecture-level Cities in Hunan Province from 2016 to 2021

Year	tfp	effch	pech	tech	sech
2016~2017	0.9322	1.0360	1.0077	0.9186	1.0281
2017~2018	0.9233	0.8991	0.7957	1.0441	1.1300
2018~2019	0.9830	1.4271	1.3896	0.7044	1.0270
2019~2020	1.0655	1.0370	1.0496	1.0110	0.9880
2020~2021	1.2797	0.9973	0.9083	1.3279	1.0979
Average	1.0367	1.0793	1.0302	1.0012	1.0542

Next, this paper explores which stage brought a decline to the Malmquist index from 2016 to 2017, 2017 to 2018, and 2018 to 2019. It can be seen from Table 3 that the decline of the Malmquist index (tfp3) in 2016-2017 and 2017-2018 was influenced by the second-stage Malmquist index (tfp2). The decline in the Malmquist index (tfp3) in 2018-2019 was influenced by the first-stage Malmquist (index).

Table 3 Average Malmquist Index of New S&T Innovation Efficiency of 14 Prefecture-level Cities in Hunan Province from 2016 to 2021

Year	Tfp1	Tfp2	Tfp3
2016~2017	1.1664	0.9432	0.9322
2017~2018	1.1678	0.8253	0.9233
2018~2019	1.0224	1.1542	0.9830
2019~2020	1.1090	0.9939	1.0655
2020~2021	0.9516	1.4424	1.2797
Average	1.0834	1.0718	1.0367

Next,this paper explore which stage affects the sharp decline of pure technical efficiency in 2017-2018 and 2020-

2021. From Table 4 and Table 5, we can see that the pure technical efficiency (pech) values in the first stage of 2017-2018 and 2020-2021 are 1.1863 respectively.

0.The pure technical efficiency (pech) values of the second stage are 1.1125 and 0.9833 respectively, so the great reduction of pure technical efficiency in the total stage is affected by the second stage and the first stage re spectively.

Table 4 Average Malmquist Index and Decomposition of S&T Innovation Efficiency of 14 Prefecture-level Cities in Hunan Province from 2016 to 2021

Year	tfp	effch	pech	tech	sech
2016~2017	1.1664	1.0879	1.0349	1.1249	1.0512
2017~2018	1.1678	1.2261	1.1863	0.9521	1.0336
2018~2019	1.0224	1.2101	1.2214	0.8352	0.9907
2019~2020	1.1090	0.9702	0.9413	1.1461	1.0308

2020~2021	0.9516	0.9407	0.9080	1.0056	1.0360
Average	1.0834	1.0870	1.0584	1.0128	1.0285

Table 5 Average Malmquist Index and Decomposition of S&T Innovation Efficiency of 14 Prefecture-level Cities in Hunan Province from 2016 to 2021

Year	tfp	effch	pech	tech	sech
2016~2017	0.9432	0.9945	0.9391	0.9447	1.0521
2017~2018	0.8253	1.1349	1.1125	0.7715	1.0281
2018~2019	1.1542	1.2839	1.0714	0.9272	1.1668
2019~2020	0.9939	1.3084	1.1319	0.7791	1.1294
2020~2021	1.4424	1.3813	0.9833	1.0458	1.4182
Average	1.0718	1.2206	1.0477	0.8937	1.1589

Figure 3 shows the change trends of Malmquist index (tfp), pure technical efficiency (pech), scale efficiency (sech), technological progress (tech) and technical efficiency (effch) of S&T innovation system of 14 prefecture-level cities in Hunan Province from 2016 to 2021. As can be seen from Figure 3, the trend of technical efficiency (effch) and pure technical efficiency (pech) of S&T innovation system of 14 prefecture-level cities in Hunan Province is highly consistent. Therefore, it can be concluded that the change of technical efficiency follows the change of pure technical efficiency during this period, and the improvement of pure technical efficiency promotes the improvement of technical efficiency. However, technological progress (tech) and pure technical efficiency (pech) and technical efficiency (effch) were roughly opposite change trends. Whenever the growth of technological progress (tech) contributed to the improvement of comprehensive innovation efficiency (tfp), both pure technical efficiency (pech) and technical efficiency (effch) showed a decline trend, which affected the growth of comprehensive innovation efficiency. The reason for this phenomenon lies in the regional differences of S&T innovation system among prefecture-level cities and regions in Hunan Province. It can also be seen from the line chart that the Malmquist index (tfp) trend line chart is roughly above the technological progress, so in summary, the trend of Malmquist index (tfp) is roughly subject to the changing trend of technological progress (tech). This also explains the reason why the Malmqusit index is not growing much, which is largely due to the lag of technological progress.

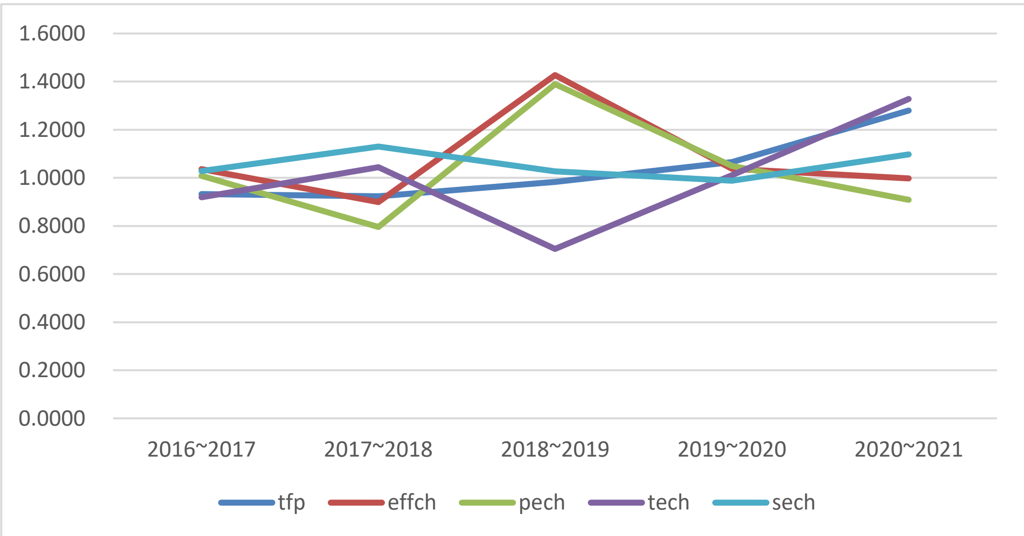

Figure 3 Change Trend Chart of tfp, effch, pech, tech and sech of Innovation System in 14 Prefecture-level Cities in Hunan Province

Table 6 is the average Malmquist index of regional S&T innovation in 14 prefecture-level cities of Hunan Province from 2016 to 2021, from which we can see the Malmquist index values (tfp3) of Changsha, Chenzhou, Hengyang, Yueyang, Zhuzhou City are all smaller than 1, and declined. The Malmquist index values (tfp3) of Changde City, Huaihua City, Loudi City, Shaoyang City, Xiangtan City, Xiangxi Prefecture, Yiyang City, Yongzhou City, and Zhangjiajie are all greater than 1, and improved. By comparing tfp1 index and tfp2 index, we can conclude that the Malmquist index of Changsha City, Chenzhou City and Yueyang City declined due to the poor efficiency of tfp2. The Malmquist index of Hengyang City and Zhuzhou City declined due to the poor efficiency value of tfp1. The tfp efficiency value of the first stage reflects the efficiency of the science and technology index from the number of R&D personnel, expenditure and patent applications. Therefore, Hengyang City, Zhuzhou City, Yongzhou City, Zhangjiajie should increase the scientific research and increase the scientific research expenditure. The tfp efficiency value of the second stage reflects the efficiency of the number of patent applications, the inverse comprehensive energy consumption and the sales revenue of new products, as well as the efficiency of putting patents into practice for the production of new products. Therefore, Changsha City, Chenzhou City, Yueyang City, Huaihua City, and Xiangxi Prefecture should improve its energy consumption efficiency and increase the number of patent applications and sales revenue from new products.

Table 6 Average Malmquist Index of S&T Innovation in 14 Prefecture-level Cities in Hunan Province from 2016 to 2021

DMU	Tfp1	Tfp2	Tfp3
Changsha City	1.1057	0.9185	0.9208
Changde City	1.1164	1.0355	1.0331
Chenzhou City	1.0521	0.9127	0.8978
Hengyang City	0.9577	0.9700	0.9013
Huaihua City	1.2865	0.9782	1.0676
Loudi City	1.0994	1.0853	1.0248
Shaoyang City	1.3009	1.1014	1.1586
Xiangtan City	1.0395	1.1619	1.0676
Xiangxi Prefecture	1.1806	0.9546	1.1164
Yiyang City	1.0120	1.0921	1.0337
Yongzhou City	0.9428	1.3668	1.2216
Yueyang City	1.0590	1.0534	0.9166
Zhangjiajie	0.9863	1.3181	1.1637
Zhuzhou City	1.0294	1.0566	0.9906

Tfp1 is the first stage, Tfp2 is the second stage, and Tfp3 is the total stage

Table 7 shows the first-stage average Malmquist index and decomposition of S&T innovation efficiency of 14 prefecture-level cities in Hunan Province from 2016 to 2021. Table 8 shows the second-stage average Malmquist index and decomposition of S&T innovation efficiency of 14 prefecture level cities in Hunan Province from 2016 to 2021. As can be seen from Table 6, the Malmquist index values (tfp3) of Changsha City, Chenzhou City, Hengyang City, Yueyang City and Zhuzhou City are all smaller than 1. Furthermore, it is known that the reason for Changsha City, Chenzhou City and Yueyang City is the poor efficiency of tfp2, and for Hengyang City and Zhuzhou City is the relatively poor efficiency value of tfp1. According to Table 7 and Table 8, Changsha City was mainly affected by the second-stage scale efficiency (sech), while Chenzhou City and Yueyang City were affected by the technological progress (tech) in the second stage. Hengyang City was mainly affected by the pure technical efficiency (pech) of the first stage, and Zhuzhou City was mainly affected by the scale efficiency (sech) of the first stage.

Table 7 Average Malmquist Index and Decomposition of S&T Innovation Efficiency of 14 Prefecture-level Cities in Hunan Province from 2016 to 2021

DMU	tfp	effch	pech	tech	sech
Changsha City	1.1057	1.0295	1.0000	1.0714	1.0295
Changde City	1.1164	1.0821	1.0730	1.0322	1.0085
Chenzhou City	1.0521	1.0676	1.0513	1.0211	1.0155
Hengyang City	0.9577	0.9488	0.9498	1.0496	0.9989
Huaihua City	1.2865	1.3890	1.3499	0.9755	1.0289
Loudi City	1.0994	1.1059	1.0587	0.9948	1.0446
Shaoyang City	1.3009	1.2934	1.2809	1.0298	1.0098
Xiangtan City	1.0395	1.0273	1.0236	1.0331	1.0035
Xiangxi Prefecture	1.1806	1.2442	1.0000	0.9304	1.2442
Yiyang City	1.0120	1.0415	1.0491	1.0041	0.9927
Yongzhou City	0.9428	0.9234	0.9271	1.0264	0.9960
Yueyang City	1.0590	1.0652	1.0572	1.0300	1.0075
Zhangjiajie	0.9863	1.0316	1.0000	0.9347	1.0316
Zhuzhou City	1.0294	0.9836	0.9963	1.0458	0.9872

Table 8 Average Malmquist Index and Decomposition of S&T Innovation Efficiency of 14 Prefecture-level Cities in Hunan Province from 2016 to 2021

DMU	tfp	effch	pech	tech	sech
Changsha City	0.9185	0.9513	1.0000	0.9652	0.9513
Changde City	1.0355	1.1118	0.9330	0.9460	1.1445
Chenzhou City	0.9127	1.1146	1.0761	0.8477	1.0585
Hengyang City	0.9700	1.1269	1.0986	0.8606	1.0605
Huaihua City	0.9782	1.2689	1.0032	0.7762	1.2404
Loudi City	1.0853	1.1237	1.0000	0.9557	1.1237
Shaoyang City	1.1014	1.3588	0.9846	0.7889	1.4321
Xiangtan City	1.1619	1.2263	1.1237	0.9541	1.0713
Xiangxi Prefecture	0.9546	1.1290	1.0000	0.8766	1.1290
Yiyang City	1.0921	1.2538	1.0941	0.8531	1.1472
Yongzhou City	1.3668	1.7708	1.1473	0.7893	1.4758
Yueyang City	1.0534	1.0753	1.0000	0.9694	1.0753
Zhangjiajie	1.3181	1.4834	1.1649	0.8535	1.2636
Zhuzhou City	1.0566	1.0935	1.0418	1.0751	1.0517

IV. Conclusion

This paper studies the evaluation of S&T innovation efficiency of 14 prefecture-level cities in Hunan Province from 2016 to 2021 by using the dynamic network DEA with a new structure, and draws the following conclusions and enlightenment: (1) From 2016 to 2021, the comprehensive innovation efficiency (tfp) of S&T innovation efficiency of 14 prefecture-level cities in Hunan Province showed a gradual improvement trend.(2) The technological progress curve is basically below the comprehensive innovation efficiency (tfp), so the trend of Malmquist index (tfp) is largely subject to the changing trend of technological progress (tech). This also explains the reason why the Malmqusit index did not improve significantly, which is largely due to the lag of technological progress. In response to this, prefecture-level cities are advised to increase the investment in S&T innovation to break through the innovation bottleneck. (3) When technology efficiency declines, scale efficiency cannot completely offset the negative impact of technology efficiency decline on comprehensive innovation efficiency, but it can partially save the decline in comprehensive innovation efficiency. Therefore, when science and technology efficiency declines, the benefits brought by scale efficiency should be firmly grasped and scientific management of scientific and technological talents should be strengthened. Furthermore, it is necessary to optimize the allocation of innovation resources and improve the utilization efficiency of innovation input. (4) `The empirical research shows that whenever the growth of technological progress (tech) contributes to the improvement of comprehensive innovation efficiency (tfp), the pure technical efficiency (pech) and technical efficiency (effch) shows a downward trend and affects the growth of comprehensive innovation efficiency. The reason for this phenomenon lies in the regional differences of S&T innovation system among 14 prefecture-level cities in Hunan Province. The productivity values of S&T innovation of Changsha City, Chenzhou City, Hengyang City, Yueyang City, and Zhuzhou City are all smaller than 1. The empirical research shows that the decline in tfp efficiency value is affected by the corresponding scale efficiency (sech) or technological progress (tech) in the corresponding stage. It can be seen that Changsha City was inhibited by the two-stage two-stage scale efficiency (sech), and Chenzhou City and Yueyang City were inhibited by the two-stage technological progress (tech). Hengyang City was mainly inhibited by the pure technical efficiency (pech) of the first stage, and Zhuzhou City was mainly inhibited by the scale efficiency (sech) of the first stage. Changsha City should support S&T innovation, strengthen scientific and technological research and development, optimize the allocation of innovation resources, improve the utilization efficiency of innovation input, and increase the utilization rate of comprehensive energy consumption. Chenzhou City and Yueyang City need to continue to develop and improve technologies, replace old technologies with new technologies, strengthen innovation of new technologies to replace old technologies, promote enterprise transformation and upgrading instead of staying in traditional technologies, enhance market vitality, and stimulate and improve the innovation power and capability of enterprises. Hengyang City should strengthen the management of technical personnel, scientific management, and strengthen support for scientific and technological innovation. Zhuzhou City should strengthen R&D personnel and internal expenditure, and improve the efficiency of patent applications, enhance the positive correlation between input and output, and improve the utilization efficiency of innovation input.

Acknowledgments

This research was funded by the Hunan Philosophy and Social Science Foundation Project no. 20YBA121，Hunan Provincial Social Science Review Committee Project

(XSP2023JJCO40

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