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The Construction and Empirical Research on the Dynamic Evaluation Model of University Science and Technology Output

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ABSTRACT We established a model based on the ''Malmquist index'' to evaluate the dynamic performance of scientific and technological innovation in seven Chinese universities, which included five categories: changes in pure technical efficiency, changes in production technology, changes in scale efficiency, changes in organizational management performance, and changes in comprehensive efficiency. Seven domestic first-class universities were studied, and empirical analysis was performed based on data related to their scientific and technological innovation during three time periods (2013-2014, 2014-2015, and 2015-2016). Our results demonstrated that the contribution rate for each index was different for each university across the three time periods, and that Chinese universities is gradually transitioning from resource allocation to technical efficiency. In this paper, we explored the transformation from effect to efficiency and static to dynamic in the evaluation of the scientific and technological output of colleges and universities, and constructed systematic and unique multi-evaluation system for the scientific and technological output of universities.

INDEX TERMS Dynamic performance, university science and technology, data envelopment analysis, enhanced Russell measure, Malmquist index.

I. INTRODUCTION

There are several methods for evaluating the scientific research of colleges and universities, and these methods are production systems that typically have multiple inputs and multiple outputs [1]. Data envelopment analysis (DEA) [2], is a mathematical linear programming-based technique to evaluate the relative performance of organizations [3], [4]. Recent years have seen a great variety of applications of DEA for use in evaluating the performances of many different kinds of entities engaged in many different activities in many different contexts in many different countries. DEA can resolve the complex (often unknown) nature of the relations between multiple inputs and multiple outputs involved in many of these activities (which are often reported in non-commeasurable units) [5]. Furthermore, this method is currently widely used by domestic and foreign scholars to evaluate the effectiveness of the scientific research of universities. Beasley used DEA to study the main factors affecting the performance of teaching and research in universities [6]. Abramo (2009) and others used the DEA method to evaluate the scientific research efficiency of Italian universities [7]. In recent years, the DEA method has also been used to evaluate the scientific research efficiency of Chinese universities. Weng and Xi used data envelopment analysis to analyze the technical efficiency of the performance evaluation of Chinese 211 universities [8]. Shen and Zhao used the DEA method to evaluate and rank the scientific research input-output performance of local universities in 31 Chinese provinces [9]. Using the DEA method, Xu's evaluation of the relative efficiency of the scientific research input-output for universities from 31 provinces and cities in China demonstrated no relationship between the relative efficiency of the scientific research in various provinces and regional economies. The research also demonstrated that high efficiency results in highly productive scientific research, which is the real developmental source of scientific research in colleges and universities [10].

Although some progress has been made in evaluating the scientific and technological outputs of colleges and universities, most research focuses on constructing an

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evaluation system based on the DEA and BCC models [11]–[15]. During the evaluation process, the volume of scientific and technological output was prioritized and its efficiency was ignored [16]–[18]. Additionally, most research has focused on static models of scientific and technological output and does not include dynamic evaluation models. Dynamically evaluating the output of science and technology is extremely important for colleges and universities to understand how their output capacity of science and technology changes, allowing for the subsequent formulation of corresponding development policies [19]–[21].

The Malmquist index was first proposed by Malmquist [22] and is used to analyze the total growth factor of a decision-making unit (DMU). It seeks to identify the changing properties related to the analysis methods of dynamic efficiency based on the data of a DMU within a certain time span. In recent years, both domestic and international scholars have begun to combine the Malmquist index with DEA theory, resulting in a production efficiency index that has been widely used in performance evaluation research [23]–[25]. It has since become the main method of evaluating the dynamic efficiency of scientific research output [26]–[29]. Flegg *et al.* (2003) found that the total technical efficiencies (pure technical efficiency, congestion efficiency and scale efficiency) of 45 British universities rose between 1980/81 and 1992/93, and that most of this increase was due to a substantial outward shift in the efficiency frontier during this period [30]. Rahimian and Soltanifar (2013) measured the relative efficiencies among different private universities in Iran, and found that there are some large gaps among various units in terms of the number of research products and the number of graduated students [31].

The Malmquist index reflects the distance between the production DMU and the optimal expected production. The index is based on the distance function and represents the magnitude of the change in the efficiency of scientific research. When the value of the index is equal to 1, scientific research efficiency remains unchanged, when the index is larger than 1, efficiency has increased, and when the index is less than 1, efficiency has decreased. The Malmquist index reflects the productivity change of a DMU over time.

In this study, we selected academic resources (including academicians, authorized doctoral degree granting points, national key disciplines, and national key laboratories), human resources (including scientific and technological personnel, and graduate students), and financial resources (including state funds and horizontal cooperation funds) as the indicators of technology investment of universities. In addition, the indicators of technology output were represented by scientific research output (including SCI papers, national awards, and invention patents). Then, based on the indicators of the technology investment and technology output of universities, we integrated the Malmquist index and the DEA model to construct a model for dynamically evaluating the scientific and technological output and performance of first-class universities, which includes the pure technical efficiency change index (PTECI), university technology change index (TCI), scale effect change index (SECI), organization management performance change index (OMPCI) and comprehensive efficiency change index (CECI). Finally, we make some recommendations based on our findings. The remainder of this paper first presents the details of the methods in section II. Then, the results are given in section III, and the discussion and conclusions are given in section IV. The paper ends by providing contributions and novelties in section V.

II. METHODS

A. CONSTRUCTION OF A DYNAMIC EVALUATION MODEL OF UNIVERSITY SCIENCE AND TECHNOLOGY OUTPUT

In this model, "n" is the number of universities participating in the evaluation, and $x_{ij}, (i = 1, 2, \ldots, m)$ and $y_{ij}, (r = 1, 2, \ldots, s)$ represent the jth, (j = 1, 2, . . . , n) values of the scientific innovation input and various output indicators, respectively. When university "0" is evaluated, its observation value combination is $(x_o, y_o), D(x_o, y_o)$, which is used to determine the efficiency value of the university under cutting-edge production technology, "$D()$". In this case, $D^a\left(x_o^b, y_o^b\right)$ represents the efficiency value of the observed value of the university, relative to the frontier production technology of phase "a" and phase "b". In this case, "a" and "b" are considered at "t" and "t+1", respectively, and they can be combined into four efficiency combinations: $D^t\left(x_o^t, y_o^t\right)$, $D^t\left(x_o^{t+1}, y_o^{t+1}\right)$, $D^{t+1}\left(x_o^t, y_o^t\right)$ and $D^{t+1}\left(x_o^{t+1}, y_o^{t+1}\right)$. These combinations are calculated using the enhanced Russell measure.

Assuming Constant Returns to Scale (CRS) [32] the enhanced Russell measure is calculated by the planning model (1)

$$\begin{aligned} D^a\left(x_o^b, y_o^b\right) &= min_{\theta,\phi,\lambda}\left(\frac{1}{m}\sum\nolimits_{i=1}^{m}\theta_i\right)\Big/\left(\frac{1}{s}\sum\nolimits_{r=1}^{s}\phi_r\right) \\ \text{s.t. } \theta_i x_{io}^b &\geq \sum\nolimits_{j=1}^{n}\lambda_j x_{ij}^a, \quad i = 1, 2, \ldots, m \\ \phi_r y_{io}^b &\geq \sum\nolimits_{j=1}^{n}\lambda_j y_{ij}^a, \quad r = 1, 2, \ldots, s \\ 0 \leq \theta_i &\leq 1\,(\forall i), \quad \phi_r \geq 1\,(\forall r), \ \lambda_j \geq 0\,(\forall j) \quad (1) \end{aligned}$$

The optimal solution is written as $(D_c^a\left(x_o^b, y_o^b\right)^*, \theta_i^*, \phi_r^*, \lambda_j^*)$. Similarly, under the hypothesis of Variable Returns to Scale (VRS) [33], it is necessary to add the constraint $\sum_{j=1}^{n}\lambda_j = 1$ to model (1). The optimal solution of the model is now written as $\left(D_v^a\left(x_o^b, y_o^b\right)^*, \theta_i^*, \phi_r^*, \lambda_j^*\right)$.

When a is equal to b, model (1) measures the efficiency of the same time period. By comparing the relative efficiency of the evaluation units in the same period with the observation data of the evaluation units composing the front edge, $D^a\left(x_o^b, y_o^b\right)^* \leq 1$. To increase discrimination, when $D^a\left(x_o^b, y_o^b\right)^* = 1$, combined with the super-efficiency model of Anderson and Petersen (1993) [34], we used the ERM super-efficiency model (2) [35] [36]. When a is unequal to b, model (1) is used to measure the intertemporal efficiency while the observation value combination of the evaluation unit $\left(x_o^b, y_o^b\right)$ is not involved in combining the observation data of all units $\left(x_j^a, y_j^a\right)$ $(j = 1, 2, \ldots, n)$ in the comparison period, which constitutes the front face. The latter case often addresses infeasible solutions [37], and the ERM super-efficiency model (2) is also needed.

Under the assumption of Constant Returns to Scale (CRS), the ERM super-efficiency model is expressed as:

$$\begin{aligned} &D^a\left(x_o^b, y_o^b\right) \\ &\quad = min_{\theta,\phi,\lambda}\left(\frac{1}{m}\sum\nolimits_{i=1}^{m}\theta_i\right)\Big/\left(\frac{1}{s}\sum\nolimits_{r=1}^{s}\phi_r\right) \\ &\quad\quad \text{s.t. } \theta_i x_{io}^b \geq \sum\nolimits_{j=1,j\neq o}^{n}\lambda_j x_{ij}^a, \quad i = 1, 2, \ldots, m \\ &\quad\quad\quad \phi_r y_{io}^b \geq \sum\nolimits_{j=1,j\neq o}^{n}\lambda_j y_{ij}^a, \quad r = 1, 2, \ldots, s \\ &\quad\quad\quad \theta_i \geq 1\,(\forall i), \quad 0 \leq \phi_r \leq 1\,(\forall r), \ \lambda_j \geq 0\,(\forall j) \quad (2) \end{aligned}$$

Similarly, under the hypothesis of Variable Returns to Scale (VRS), we must add the constraint $\sum_{j=1,j\neq o}^{n}\lambda_j = 1$ to model (2).

B. MODELS OF FIVE MEASUREMENT INDEXES

1) INDEX OF PURE TECHNICAL EFFICIENCY CHANGE (PTECI)

Technical efficiency reflects the proliferation of technical organizations and the improvement of management practices [38]. It reflects how the efficient production of technology affects the stable use of technology. The higher the technical efficiency is, the more efficient the technical production. Since this index relies on organizational systems, particularly the organization's technology introduction and digestion and absorption systems, changes in technical efficiency reflect the improvement, stagnation, or regression of the effectiveness of the organization's technical policies and systems.

$$\begin{aligned} &\text{PTECI} = \left[\text{APTECI}\cdot\text{RPTECI}^{\text{t+1}}\cdot\text{RPTECI}^{\text{t}}\right]^{1/3} \\ &\quad \text{s.t. APTECI} = D_v^{t+1}\left(x_o^{t+1}, y_o^{t+1}\right)/D_v^t\left(x_o^t, y_o^t\right) \\ &\quad\quad \text{RPTECI}^{\text{t}} = D_v^t\left(x_o^{t+1}, y_o^{t+1}\right)/D_v^t\left(x_o^t, y_o^t\right) \\ &\quad\quad \text{RPTECI}^{\text{t+1}} = D_v^{t+1}\left(x_o^{t+1}, y_o^{t+1}\right)/D_v^{t+1}\left(x_o^t, y_o^t\right) \end{aligned} \quad (3)$$

2) UNIVERSITY TECHNOLOGY CHANGE INDEX (TCI)

Like other traditional production organizations, changes in production technology (levels) are the performance indicators most important to innovative production organizations such as universities, and reflect the improvement, stagnation, or deterioration of the key conditions determining the production of scientific and technological innovation by universities (such as the quality of scientific research personnel and the level of scientific research equipment).

$$\text{TCI} = \left[\frac{D_v^t\left(x_o^{t+1}, y_o^{t+1}\right)}{D_v^{t+1}\left(x_o^{t+1}, y_o^{t+1}\right)}\cdot\frac{D_v^t\left(x_o^t, y_o^t\right)}{D_v^{t+1}\left(x_o^t, y_o^t\right)}\right]^{1/2} \quad (4)$$

3) SCALE EFFECT CHANGE INDEX (SECI)

The scale efficiency change index reflects the comprehensive changes in the scale effect of colleges and universities under evaluation in period "t+1" relative to period "t", and is divided into three categories: index is equal to 1, is larger than 1, and is less than 1. If the index is equal to 1, it means that the state of the returns to scale is unchanged; if index is less than 1, it means that the state of the returns to scale has slowed (i.e., if the original returns to scale have increased, the current rate of increase has slowed); and if index is larger than 1, it indicates that the state of the returns to scale has improved (i.e., if the original scale returns increased, the increment rate increased).

$$\begin{aligned} &\text{SECI} \\ &\quad = \left[\text{ASECI}\cdot\text{RSECI}^{\text{t}}\cdot\text{RSECI}^{\text{t+1}}\right]^{1/3} \\ &\quad\quad \text{s.t. ASECI} = \frac{D_c^{t+1}\left(x_o^{t+1}, y_o^{t+1}\right)/D_v^{t+1}\left(x_o^{t+1}, y_o^{t+1}\right)}{D_c^t\left(x_o^t, y_o^t\right)/D_v^t\left(x_o^t, y_o^t\right)} \\ &\quad\quad\quad \text{RSECI}^{\text{t}} = \frac{D_c^t\left(x_o^{t+1}, y_o^{t+1}\right)/D_v^t\left(x_o^{t+1}, y_o^{t+1}\right)}{D_c^t\left(x_o^t, y_o^t\right)/D_v^t\left(x_o^t, y_o^t\right)} \\ &\quad\quad\quad \text{RSECI}^{\text{t+1}} = \frac{D_c^{t+1}\left(x_o^{t+1}, y_o^{t+1}\right)/D_v^{t+1}\left(x_o^{t+1}, y_o^{t+1}\right)}{D_c^{t+1}\left(x_o^t, y_o^t\right)/D_v^{t+1}\left(x_o^t, y_o^t\right)} \end{aligned} \quad (5)$$

4) ORGANIZATION MANAGEMENT PERFORMANCE CHANGE INDEX (OMPCI)

As the scale of colleges and universities expands, the operational process of the technological innovation at colleges and universities is becoming increasingly more complicated. Adequate resources and technology do not equal better results, because benefits are also subject to the performance impact of organizational management (including non-institutional and soft policy-based management methods, and institutional and hard policy-based management methods). The aforementioned technical efficiency change index reflects the improvement or innovation of institutional and hard policy management methods. This paper uses the organizational management performance change index to reflect the evaluation of non-institutional and soft policy management methods in the improvement or innovation of universities.

$$\text{OMPCI} = \left[\frac{D_v^t\left(x_o^{t+1}, y_o^{t+1}\right)}{D_v^t\left(x_o^t, y_o^t\right)}\cdot\frac{D_v^{t+1}\left(x_o^{t+1}, y_o^{t+1}\right)}{D_v^t\left(x_o^t, y_o^t\right)}\right]^{1/2} \quad (6)$$

5) COMPREHENSIVE EFFICIENCY CHANGE INDEX (CECI)

In complex organizations, institutional and policy management are the primary methods of management and drive technological innovation. Based on this, we used the geometric

TABLE 1. The composite weight of each sub-index relative to the overall goal.

	First-level Indicators	First-level Indicators Weights	Statistical Indicators	Statistical Indicators Weights	Composite Weights Pi
Technology investment	Academic resources	0.33	Number of academics	0.25	0.0833
			Number of authorized doctoral degrees	0.25	0.0833
			Number of key national disciplines	0.25	0.0833
			Number of key national laboratories	0.25	0.0833
	Human resources	0.33	Number of scientific and technological personnel	0.5	0.1667
			Number of graduate students	0.5	0.1667
	Financial resources	0.33	State funds	0.5	0.1667
			Horizontal cooperation funds	0.5	0.1667
Technology output	Scientific research output	1	Number of SCI papers	0.2	0.2
			National awards	0.6	0.6
			Number of invention patents	0.2	0.2

mean method to synthesize the three dynamic performance indexes of pure technical efficiency change, technical (level) change, and scale effect change to analyze the comprehensive dynamic efficiency change (CECI) of the tested universities.

$$CECI = [PTECI \cdot TCI \cdot SECI]^{1/3} \tag{7}$$

The basic properties of the five indexes constructed above are as follows:

(1) The higher the value is, the quicker the improvement in performance.

(2) If the index value is less than 1, the current index performance has deteriorated (regression); if the index value is equal to 1, the index performance has stagnated; and if the index value is larger than 1, the index performance has improved (growth).

C. INDEX SELECTION

In this model, there are several indicators referring to investment in scientific and technological innovation. To comprehensively consider each input factor, we measured the scientific and technological innovation input of participating universities according to the following three categories. The first category was academic resources: the scores of four measurable indicators, including the number of academics, the number of authorized doctoral degrees, the number of key national disciplines, and the number of key national laboratories were all weighted (Table 1). The second category was human resources: the scores of two measurable indicators including the number of personnel and graduate students involved in scientific and technological activities, are weighted by their weights (Table 1). The third category was funding resources: the scores of two measurable indicators based on state and horizontal cooperation funds were weighted according to their weights (Table 1). The data used were obtained from the 2013-2016 "Compilation of Scientific and Technical Statistics of Chinese Higher Education Institutions", official university websites, and relevant databases.

The output factors include academic achievements related to innovative activities for universities. Three indicators were selected as measurement indicators for quantifying the values of scientific and technological output, including the number of SCI papers, the number of national awards, and the number of patents.

For these indicators, the score of each measurable index was equal to the actual observed value or statistical value of the index divided by MAX (actual observation value or statistical value of the indicators of 7 universities) multiplied by 100. The input-oriented measurable indicators were equally weighted, and the average method was used to obtain the scores of the three scientific innovation input indicators. The secondary indicator weights were allocated according to the average method. For the three indicators of scientific and technological output, we estimated their weights using the analytic hierarchy process (AHP) [39], which uses the pairwise judgment matrix constructed using experts' scores. The resulting values for the number of SCI papers, number of national awards, and number of patents are 0.2, 0.6,

TABLE 2. The scientific and technological input and output indicators of seven domestic universities in 2013-2016.

Years	University	Academic Resources				Human Resources		Funding Resources (Thousand Yuan)		Technology Output		
		Number of Academicians	Doctoral Degree Authorization Points	Number of National Key Disciplines	Number of State Key Laboratories	Scientific and Technical Personnel	Postgraduate	State Allocated Funds	Horizontal Cooperation Funds	SCI Papers	National Awards	Number of Invention Patents
2013-2014	PKU	44	49	18	14	4354	6056	1720037	413691	70983	8	298
	THU	59	49	22	11	3860	8682	3013831	1137711	67086	15	1480
	FDU	21	36	11	5	2032	3820	1534705	219985	51997	0	308
	ZJU	17	57	14	10	4491	6352	2192388	959511	75170	18	1423
	SJTU	24	41	9	5	3046	8013	2139915	669025	74505	5	672
	NJU	20	38	8	7	4491	6352	793796	365202	41328	2	310
	SCU	8	45	5	4	2277	5940	761610	1132622	46212	4	359
2014-2015	PKU	44	49	18	14	4570	6427	1866530	446846	69975	3	305
	THU	59	49	22	11	4780	9131	2862096	1263428	65867	17	1480
	FDU	21	36	11	5	2166	3955	1203220	229095	49906	2	261
	ZJU	17	57	14	10	7695	13686	2400530	1107921	73601	13	1489
	SJTU	24	41	9	5	3065	9040	1885778	767845	71969	7	822
	NJU	20	38	8	7	3773	5038	872674	408221	40264	2	319
	SCU	8	45	5	4	1811	3248	737481	997813	45087	3	409
2015-2016	PKU	51	49	18	14	4852	6961	1935228	440332	68981	10	333
	THU	63	49	22	11	4743	9154	3301303	1586283	64564	19	1629
	FDU	22	36	11	5	2682	4153	1933859	233932	47612	3	290
	ZJU	21	57	14	10	7583	13952	2626832	1266561	72251	8	1700
	SJTU	27	41	9	5	5441	8979	1948420	717688	69096	7	1210
	NJU	21	38	8	7	3991	5278	944817	519251	39191	3	332
	SCU	9	45	5	4	1743	3251	900283	863582	45087	5	459

Notes: PKU: Peking University, THU: Tsinghua University, FDU: Fudan University, ZJU: Zhejiang University, SJTU: Shanghai Jiaotong University, NJU: Nanjing University, SCU: Sichuan University

and 0.2, respectively. All of the specific weights of each sub-indicator are shown in Table 1.

III. RESULT

A. CALCULATION OF THE MEASUREMENT INDEXES OF 7 UNIVERSITIES

This study assessed Peking University (PKU), Tsinghua University (THU), Fudan University (FDU), Zhejiang University (ZJU), Shanghai Jiaotong University (SJTU), Nanjing University (NJU), and Sichuan University (SCU). The first six of these universities are among the top seven universities according to the QS World University Rankings, the US NEWS Ranking, the ARWU Ranking, and The Times Ranking. All seven universities are members of the C9 college alliance and are the backbone of China's world-class universities. Sichuan University, located in Southwest China, is an important force in the second-class of China's universities.

The data used for academic resources, human resources, and financial resources come from the "Science and Technology Statistics of Chinese Universities" and official university websites. The data for SCI papers used in the scientific and technological output data come from the WEB OF SCIENCE database, the number of national awards comes from the official website of the National Science and Technology Award Office, and the number of patents comes from the Derwent Innovation Platform (Derwent Innovation)-Clarivate. All data were cleaned, and three time windows (2013-2014, 2014-2015, and 2015-2016) were selected as periods for the comparative analysis (Table 2).

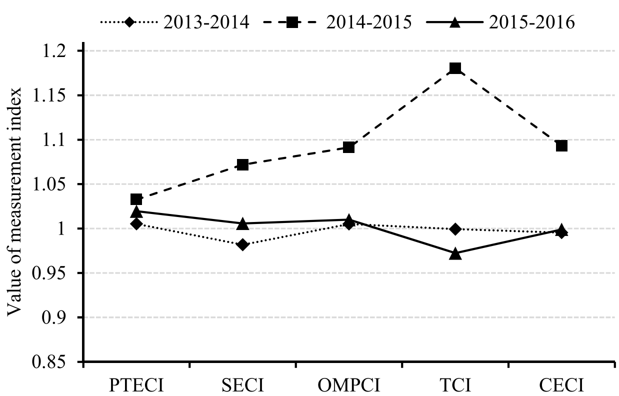

FIGURE 1. Changes and comparison of the average performance of each measurement index.

The index data in Table 1 are calculated based on model (1) and model (2), while the five formulas of the measurement indexes were used to obtain the pure calculated efficiency change index, scale change index, organizational management performance change index, technology (level) change index, and comprehensive efficiency change. The values of these indices are shown in Table 3.

The average values of the five measurement indexes of seven universities (Figure 1) demonstrate that in 2013-2014 the values of the pure technical efficiency change index (PETCI) and organization management performance change index (OMPCI) are greater than 1, and that the values of the scale reward change index (SECI), technical change index (TCI), and comprehensive efficiency change index (CECI)

TABLE 3. Measured values of THE five evaluation indicators of the seven universities.

Years	University	PTECI	SECI	OMPCI	TCI	CECI
2013-2014	PKU	0.996	0.998	0.996	1.002	0.999
	THU	1.001	0.993	1.000	0.996	0.997
	FDU	1.002	0.924	1.002	1.001	0.975
	ZJU	1.008	0.995	1.007	0.997	1.000
	SJTU	1.030	0.952	1.031	1.004	0.995
	NJU	1.000	1.011	1.001	1.003	1.005
	SCU	1.000	1.002	0.998	0.993	0.998
2014-2015	PKU	0.985	1.027	1.019	1.107	1.039
	THU	1.096	1.053	1.147	1.147	1.098
	FDU	1.196	0.894	1.360	1.473	1.163
	ZJU	0.901	1.006	0.942	1.140	1.011
	SJTU	1.062	1.028	1.128	1.200	1.094
	NJU	0.888	1.285	0.925	1.128	1.088
	SCU	1.141	1.264	1.180	1.106	1.168
2015-2016	PKU	1.088	0.996	1.099	1.031	1.038
	THU	0.990	1.015	0.992	1.007	1.004
	FDU	0.841	1.025	0.825	0.943	0.933
	ZJU	1.027	0.983	1.018	0.976	0.995
	SJTU	1.021	0.954	1.001	0.943	0.972
	NJU	1.067	0.924	1.001	0.825	0.934
	SCU	1.130	1.158	1.169	1.106	1.131

are less than 1. In 2014-2015, the values of all five measurement indexes were greater than 1. During 2015-2016, the values of the PETCI, SECI, and OMPCI were all greater than 1, and the values of the TCI and CECI were less than 1. In 2013-2016, the overall innovation level of the tested universities demonstrated a continually improving trend.

The average values of the five measurement indexes of the seven universities (Figure 1) demonstrate that in 2013-2014 the values of the pure technical efficiency change index (PETCI) (1.005) and organization management performance change index (OMPCI) (1.010) are greater than 1, and that the values of scale reward change index (SECI) (0.982), technical change index (TCI) (0.999), and comprehensive efficiency change index (CECI) (0.999) are less than 1. In 2014-2015, the values of all five measurement indexes (PTECI: 1.033, SECI: 1.072, OMPCI: 1.091, TCI: 1.180, and CECI: 1.093) were greater than 1. During 2015-2016, the values of PETCI (1.020), SECI (1.006), and OMPCI (1.010) were all greater than 1, and the values of TCI (0.972) and CECI (0.999) were less than 1. In 2013-2016, the overall innovation level of the tested universities demonstrated a continually improving trend.

B. COMPARISON OF THE MEASUREMENT INDEXES AMONG SEVEN UNIVERSITIES

With respect to the pure technology efficiency change index (PTECI) (Figure 2A), in 2013 to 2014, only the PTECI of Peking University (0.996) was less than 1, and the PTECI was greater than 1 for the other six universities (THU: 1.001, FDU: 1.002, ZJU: 1.008, SJTU: 1.030, NJU: 1.000, and SCU: 1.000). In 2014-2015, the PTECIs of Peking University (0.985), Zhejiang University (0.901), and Nanjing University (0.888) were less than 1; and the PTECI was greater than 1 for the remaining four universities (THU: 1.096, FDU: 1.196, SJTU: 1.062, and SCU: 1.141). In 2015-2016, the PTECIs of Tsinghua University (0.990) and Fudan University (0.841) were less than 1, and the PTECI was greater than 1 for the other five universities (PKU: 1.088, ZJU: 1.027, SJTU: 1.021, NJU: 1.067, and SCU: 1.130). These results indicate that the PTECI of Peking University is gradually improving, the PTECIs of Tsinghua University and Fudan University are both trending downward, the PTECIs of Zhejiang University and Nanjing University trended upward-downward-upward from 2013-2016, and the PTECIs of Shanghai Jiaotong University and Sichuan University continued to improve.

With respect to the SECI (Figure 2B), in 2013 and 2014 (1.011) only Nanjing University and Sichuan University (1.002) had a SECI greater than 1 while the SECI of the remaining five universities (PKU: 0.998, THU: 0.993, FDU: 0.924, ZJU: 0.995, and SJTU: 0.952) was less than 1. In 2014-2015, only Fudan University's SECI (0.894) was less than 1 while the SECIs values of the remaining six universities (PKU: 1.027, THU: 1.053, ZJU: 1.006, SJTU: 1.028, NJU: 1.285, and SCU: 1.264) were all greater than 1. In 2015-2016, the SECIs of Tsinghua University (1.015), Fudan University (1.025), and Sichuan University (1.158) were all greater than 1. The SECIs of the remaining four universities (PKU: 0.996, ZJU: 0.983, SJTU: 0.954, and NJU: 0.924) were all less than 1. These results demonstrate that the TCE Index of Tsinghua University,

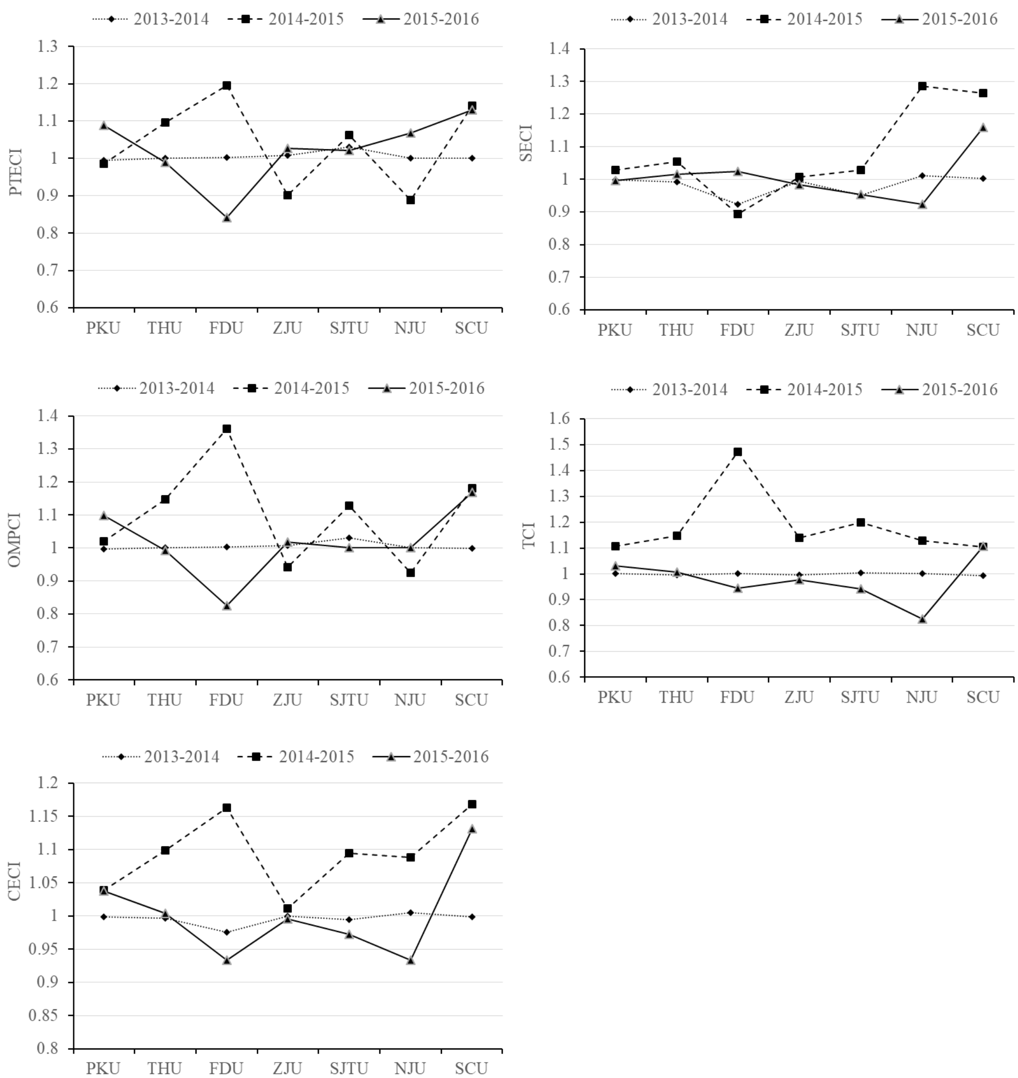

FIGURE 2. Comparison of the changes in the measurement indexes among the seven universities.

Fudan University, and Sichuan University all continued to improve; the SECIs of Peking University, Zhejiang University, and Shanghai Jiaotong University all trended downward-upward-downward; and the SECI of Nanjing University continued to improve in 2013-2015 but decreased in 2015-2016.

With respect to the OMPCI (Figure 2C), in 2013-2014, the index values of Peking University (0.996) and Sichuan University (0.998) were less than 1 while the index values of the remaining five universities (THU: 1.000, FDU: 1.002, ZJU: 1.007, SJTU: 1.031, and NJU: 1.001) were all greater than 1; in 2014-2015, the OMPCIs of Zhejiang University (0.942) and Nanjing University (0.925) were less than 1, and the OMPCIs of the remaining five universities (PKU: 1.019, THU: 1.147, FDU: 1.360, SJTU: 1.128, and SCU: 1.180) were all greater than 1. In 2015-2016, the OMPCIs of Tsinghua University (0.992) and Fudan University (0.825) were less than 1, and the OMPCIs of the remaining five universities (PKU: 1.099, ZJU: 1.018, SJTU: 1.001, NJU: 1.001, and SCU: 1.169) were all greater than 1. These results demonstrate that the OMPCIs of Shanghai Jiaotong University and Sichuan University are continuously improving, the OMPCIs of Peking University is gradually improving, the OMPCIs of Tsinghua University and Fudan University improved in the early stage, but decreased later on, and the OMPCIs of Zhejiang University and Nanjing University trended upward-downward-upward.

With respect to the TCI (Figure 2D), in 2013-2014, the index values of Tsinghua University (0.996), Zhejiang University (0.997), and Sichuan University (0.993) were all less than 1, and the index values of the remaining four universities (PKU: 1.002, FDU: 1.001, SJTU: 1.004, and NJU: 1.003) were all greater than 1. In 2014-2015, the TCIs of all seven universities (PKU: 1.107, THU: 1.147, FDU: 1.473, ZJU: 1.140, SJTU: 1.200, NJU: 1.128, and SCU: 1.106) were greater than 1. In 2015-2016, the TCIs of Peking

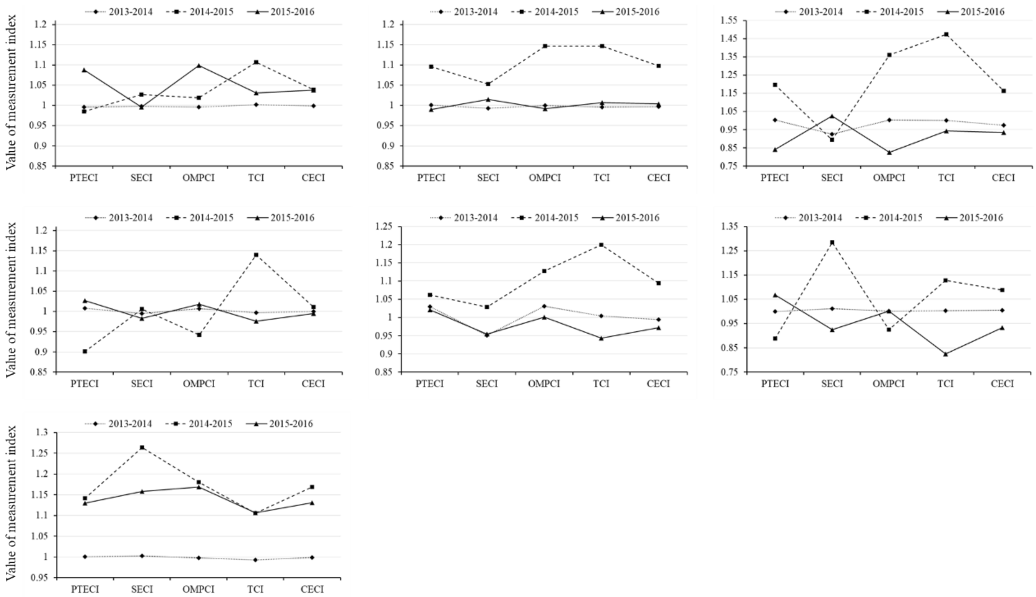

FIGURE 3. Comparison of the changes in the measurement indexes of the seven universities during 2013-2016.

University (1.031), Tsinghua University (1.007), and Sichuan University (1.106) were all greater than 1, and the TCIs of the remaining four universities (FDU: 0.943, ZJU: 0.976, SJTU: 0.943, and NJU: 0.825) were all less than 1. These results demonstrate that the TCIs of Peking University is continuously improving; the TCI of Tsinghua University and Sichuan University are both gradually improving; the TCIs of Fudan University, Shanghai Jiaotong University, and Nanjing University improved in the early period and decreased in the later period; and the TCIs of Zhejiang University trended downward-upward-downward.

With respect to the CECI (Figure 2E), in 2013-2014, only Zhejiang University (1.000) and Nanjing University (1.005) had an index value greater than 1 while the other five universities (PKU: 0.999, THU: 0.997, FDU: 0.975, SJTU: 0.995, and SCU: 0.998) had index values less than 1. In 2014-2015, the CECIs of all seven universities (PKU: 1.039, THU: 1.004, FDU: 1.163, ZJU: 1.011, SJTU: 1.094, NJU: 1.088, and SCU: 1.168) were greater than 1. In 2015-2016, the CECIs of Peking University (1.038), Tsinghua University (1.004), and Sichuan University (1.131) were all greater than 1 and the CECIs of the remaining four universities (FDU: 0.933, ZJU: 0.995, SJTU: 0.972, and NJU: 0.934) were all greater than 1. These results demonstrate that the CECIs of Peking University, Tsinghua University, and Sichuan University are all gradually improving; the CECIs of Zhejiang University and Nanjing University continuously improved in the early stages; the CECIs of Fudan University and Shanghai Jiaotong University decreased in the later stages; and the CECIs of Fudan University and Shanghai Jiaotong University trended downward-upward-downward.

C. COMPARISON OF THE MEASUREMENT INDEXES OF SEVEN UNIVERSITIES IN 2013-2016

We next analyzed the index changes at each university during the three periods. As shown in Figure 3, Tsinghua University, Shanghai Jiaotong University, and Sichuan University had better PETCIs, SECIs, OMPCIs, TCIs, and CECIs in 2014-2015 (THU: 1.096, 1.053, 1.147, 1.147, and 1.098, respectively; SJTU: 1.062, 1.028, 1.128, 1.200, and 1.094, respectively; and SCU: 1.141, 1.264, 1.180, 1.106, and 1.168, respectively) than in 2013-2014 (THU: 1.001, 0.993, 1.000, 0.996, and 0.997, respectively; SJTU: 1.030, 0.952, 1.031, 1.004, and 0.995, respectively; SCU: 1.000, 1.002, 0.998, 0.993, and 0.998, respectively) and 2015-2016 (THU: 0.990, 1.015, 0.992, 1.007, and 1.004, respectively; SJTU: 1.021, 0.954, 1.001, 0.943, and 0.972, respectively; SCU: 1.130, 1.158, 1.169, 1.106, and 1.131, respectively). Fudan University had better index values in 2014-2015 (PTECI: 1.196, OMPCI: 1.360, TCI: 1.473, and CECI: 1.163) than in 2013-2014 (PTECI: 1.002, OMPCI: 1.002, TCI: 1.001, and CECI: 0.975) and 2015-2016 (PTECI: 0.841, OMPCI: 0.825, TCI: 0.943, and CECI: 0.933) with the exception of its SECI, which was worse in 2014-2015 (0.894) than in 2013-2014 (0.924) and 2015-2016 (1.025). No dynamic trends were observed in the five indexes for Peking University, Zhejiang University, and Nanjing University during the three time periods.

These results indicate that the scientific and technological innovation capabilities of Peking University, Tsinghua University, and Sichuan University show an increasing trend, while the technological innovation capabilities of the other four universities are unclear.

TABLE 4. Calculation results of Pearson's correlation coefficient between various evaluation indicators.

Index	2013-2014				2014-2015				2015-2016			
	PTECI	SECI	OMPCI	TCI	PTECI	SECI	OMPCI	TCI	PTECI	SECI	OMPCI	TCI
SECI	-0.444				-0.307				0.198			
	(-0.703)				(-0.286)				0			
OMPCI	0.996**	-0.454			0.973**	-0.431			0.956**	0.431		
	(0.937**)	(-0.536)			(1.000**)	(-0.286)			(0.937**)	-0.09		
TCI	0.378	-0.359	0.453		0.588	-0.645	0.760*		0.326	0.840*	0.588	
	-0.198	(-0.107)	-0.429		-0.321	(-0.536)	-0.321		-0.505	-0.685	-0.645	
CECI	-0.053	0.909**	-0.054	-0.1	0.826*	0.171	0.805*	0.489	0.671	0.820*	0.852**	0.898**
	(-0.450)	(0.857**)	(-0.250)	-0.036	(0.857**)	-0.214	(0.857**)	-0.107	-0.679	-0.429	(0.775*)	(0.937**)

Note: * and ** indicate significant (two-tailed) at the 1% and 5% levels, respectively. The numbers in parentheses are the calculation results of Spearman's rho rank correlation coefficient between each evaluation index.

D. CORRELATION ANALYSIS OF THE MEASUREMENT INDEXES

In the early stage of the evaluation (2013-2014), we observed no statistically significant correlation between the "PTECI ($r = -0.053$, $p = 0.91$), OMPCI ($r = -0.054$, $p = 0.91$), and TCI ($r = -0.1, p = 0.83$)" and the CECI (Table 4), indicating that Chinese universities contribute little to improving discipline innovation efficiency via their systems, management, or technology. The significant correlation between the CECI and SECI indicates that improvements in the efficiency of the scientific and technological innovation at Chinese universities during the study period are primarily related to their resource allocation. However, by 2014-2015, the relationship between the resource allocation and the rate of scientific and technological innovation (SECI vs CECI: $r = 0.171$, $p = 0.71$) became less relevant. Instead, the institutions and management of these universities have made greater contributions to technological innovation (PTECI vs CECI: $r = 0.826, p = 0.02$; and OMPCI vs CECI: $r = 0.805, p = 0.03$); and by 2015-2016, the scientific innovation of universities was jointly driven by the resource allocation (SECI vs CECI: $r = 0.820$, $p = 0.02$), organizational management (OMPCI vs CECI: $r = 0.852$, $p = 0.01$) and technological progress (TCI vs CECI: $r = 0.898$, $p = 0.01$). This indicated that the role of the system was gradually weakened (PTECI vs CECI: $r = -0.679$, $p = 0.10$).

IV. DISCUSSION and CONCLUSION

(1) There is still a gap between Chinese first-class universities and world-class universities, and an effective model to evaluate scientific and technological output is urgently needed to assess university output efficiency. Traditional data envelopment analysis (DEA) is a widely employed approach designed to assess the relative efficiency of various universities, however, it can't handle imprecise data and assumes that the data for all inputs and outputs are known exactly [40]. Moreover, DEA is a static performance evaluation methodology. In this study, we shunned the traditional radial measurement DEA and BCC models in favor of an improved Enhanced Russell Measure. Concretely, the integrated data envelopment analysis (DEA) and Malmquist productivity index (MPI) used to evaluate the performance of decision making units (DMUs) can go beyond static performance to detect the temporal variations resulting from efforts for betterment by using historic data panels [41]. We used this integrated evaluation methodology to establish an effective dynamic evaluation model for the scientific and technological output of universities and the intention of the study was to propose a national-scale comparative measurement of university technical and allocative efficiency. In this study, we used five performance indexes, (pure technology efficiency change, production technology change, scale effect change, organizational management performance change, and comprehensive efficiency change) to evaluate the dynamic trends of the scientific and technological input and output capacities of domestic first-class universities.

(2) To verify the effectiveness of the model, we selected seven domestic universities for model testing and dynamically evaluated the scientific and technological output of these universities from 2013-2016. Based on the index changes of each university during three periods (2013-2014, 2014-2015, and 2015-2016), we observed improvements in the overall level of innovation of Peking University, Tsinghua University, and Sichuan University. The scientific and technological innovation capabilities of these universities demonstrated continuous growth, the overall technological innovation capabilities of the remaining universities were uncertain, and the dynamic change between years was not obvious. Improvement and deterioration trends alternately appear. Our research results confirmed the efficiency and practicality of the model we constructed.

(3) This study demonstrated that the innovation output of Chinese universities is related to the input in different periods. In the early period (2013-2014), the innovation output of Chinese universities was primarily related to the resource allocation of universities. Contributions to the system and management of universities gradually increased (2014-2015); however, in the latest stage (2015-2016), the innovation output of Chinese universities was determined by the resource allocation, organization management, and technology, and only the role of the system in it gradually weakened. This study demonstrates that the current institutionalization of colleges and universities in China has achieved significant results and that innovation output is related to resource allocation and technological breakthroughs. We recommend that universities continue to strengthen their resource allocation, invest in their respective advantages, increase their input indicators such as human resources and financial resources, and strengthen the evaluation of output indicators such as theses and patents to measure technological progress.

V. CONTRIBUTIONS and NOVELTIES

A. EXPLORE THE TRANSFORMATION FROM EFFECT TO EFFICIENCY AND STATIC TO DYNAMIC IN THE EVALUATION OF THE SCIENTIFIC AND TECHNOLOGICAL OUTPUT OF COLLEGES AND UNIVERSITIES

As one of the subjects of scientific and technological innovation including in research papers and patents, colleges and universities play a key role in the national innovation system of ''industry-university-research'' or ''industry-university-research-government''. Therefore, to effectively estimate the quality of the innovation process, we should combine the input and output, and pay attention to the quantity of output and the efficiency of output, which represents the relative relationship between the input and output. When evaluating of the scientific and technological output of colleges and universities, most previous studies focused on the production of papers, patents, achievement transformation, etc. rather than their efficiency. In addition, these studies pay more attention to the empirical research on the static frontier performance of the cross-section of S&T innovation activities in colleges and universities, instead of the dynamic performance. However, measurement using a dynamic evaluation can provide insight into the changing behavior of S&T innovation in colleges and universities to formulate more targeted management strategies. In our study, we combined the Malmquist index with the DEA model and established a dynamic performance model of scientific and technological output, which pay more attention to efficiency. This multiangle model estimates the dynamic performance index of science and technology innovation activities, which will perfect the quantitative evaluation of the higher education system, further promote the administrative departments' timely tracking of the development trends of colleges and universities, and adjust the development strategy and planning for scientific research.

B. SYSTEMATIC AND UNIQUE MULTI-EVALUATION SYSTEM FOR THE SCIENTIFIC AND TECHNOLOGICAL OUTPUT OF UNIVERSITIES

From the perspective of scientific and technological innovation input and innovation output, this research systematically builds a unique multi-university scientific and technological output evaluation system to compensate for the shortcomings in China's existing scientific and technological output evaluation system, which is mostly based on papers and patents, and less considers multiple scientific and technological evaluation elements. To fully consider the input elements, this article measures the investment in scientific and technological innovation of universities participating in the evaluation from the following three comprehensive aspects. The first is academic resources: the scores of 4 measurable indicators, including the number of academicians, the number of authorized doctoral degrees, the number of national key disciplines, and the number of national key laboratories, are weighted. The second is human resources: the scores of two measurable indicators including the number of scientific and technological activities and the number of graduate students are weighted. The third is funding resources: the scores of two measurable indicators, including the state allocated funds and horizontal cooperation funds, are weighted. In terms of innovation output, due to the innovation activities for universities, the output only includes academic results. In addition, considering that the level of scientific research of colleges and universities is relatively outstanding, the number of SC1 papers, the number of national awards, and the number of invention patents are finally selected as the measurement indicators, which are weighted and aggregated into the measurement value of scientific and technological output according to their weights.

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REFERENCES

[1] W. Q. Liao, L. Liang, and M. L. Song, ''Analysis of efficiency of colleges and universities' scientific research based on Malmquist index,'' *Syst. Eng.*, vol. 29, pp. 64–69, Jul. 2011.

[2] M. J. Li and G. H. Chen, ''A review on the research and application of DEA,'' *Eng. Sci.*, vol. 5, pp. 88–94, Jun. 2003.

[3] E. Jordi, C. Pley, M. Jowett, G. J. Abou Jaoude, and H. Haghparast-Bidgoli, ''Assessing the efficiency of countries in making progress towards universal health coverage: A data envelopment analysis of 172 countries,'' *BMJ Global Health*, vol. 5, no. 10, Oct. 2020, Art. no. e002992.

[4] Y. Ji and C. Lee, ''Data envelopment analysis,'' *Stata J.*, vol. 10, pp. 267–280, Jul. 2010.

[5] W. D. Cook, ''Introduction to data envelopment analysis and its uses: With-DEA solver software and references,'' *Interfaces*, vol. 36, pp. 474–475, Sep./Oct. 2006.

[6] J. E. Beasley, ''Determining teaching and research efficiencies,'' *J. Oper. Res. Soc.*, vol. 46, no. 4, pp. 441–452, Apr. 1995.

[7] G. Abramo, C. A. D'Angelo, F. Di Costa, and M. Solazzi, ''University–industry collaboration in Italy: A bibliometric examination,'' *Technovation*, vol. 29, nos. 6–7, pp. 498–507, Jun. 2009.

[8] M. L. Weng and Q. Xi, "Based on data envelopment analysis performance evaluation of institutions of higher education-take 211 institutions as the example," *Sci. Econ. Soc.*, vol. 31, pp. 75–81, Dec. 2013.
[9] L. H. Shen and Y. Zhao, "An evaluation on the performance of scientific researches in local colleges and universities based on data envelopment analysis," *Higher Eng. Educ. Res.*, pp. 147–151, Jun. 2016.
[10] J. Xu, "An evaluation of relative input–output efficiency of research in higher education institutions in China: A data envelopment analysis (DEA)," *Tsinghua J. Educ.*, vol. 30, pp. 76–80, Apr. 2009.
[11] T. Rosenmayer, "Using data envelopment analysis: A case of universities," *Rev. Econ. Perspect.*, vol. 14, no. 1, pp. 34–54, Mar. 2014.
[12] A. González-Garay, C. Pozo, Á. Galán-Martín, C. Brechtelsbauer, B. Chachuat, D. Chadha, C. Hale, K. Hellgardt, A. Kogelbauer, O. K. Matar, N. McDowell, N. Shah, and G. Guillén-Gosálbez, "Assessing the performance of UK universities in the field of chemical engineering using data envelopment analysis," *Educ. Chem. Eng.*, vol. 29, pp. 29–41, Oct. 2019.
[13] M. Salas-Velasco, "The technical efficiency performance of the higher education systems based on data envelopment analysis with an illustration for the Spanish case," *Educ. Res. Policy Pract.*, vol. 19, no. 2, pp. 159–180, Jun. 2020.
[14] D. Visbal-Cadavid, M. Martínez-Gómez, and F. Guijarro, "Assessing the efficiency of public universities through DEA. A case study," *Sustainability*, vol. 9, no. 8, p. 1416, Aug. 2017.
[15] M. Toloo and S. Nalchigar, "A new integrated DEA model for finding most BCC-efficient DMU," *Appl. Math. Model.*, vol. 33, no. 1, pp. 597–604, Jan. 2009.
[16] G. S. Lu and L. Liu, "Research on efficiency and development trend of natural science in universities directly under the ministry of education," *Res. Higher Educ. Eng.*, pp. 12–16, Jan. 2006.
[17] S. M. Sun, H. L. Xiang, and B. Lan, "The efficiency analysis on input and output of science research in regional universities on basis of DEA," *Sci. Sci. Manage. S.T*, vol. 28, pp. 18–21, Jul. 2007.
[18] J. Zhou, L. J. Wang, and X. J. Shi, "A study on institutional efficiency and scale efficiency of universities' S&T innovation in different regions of China," *R D Manage.*, vol. 17, pp. 109–117, Feb. 2005.
[19] J. Guan and K. Chen, "Modeling macro-R&D production frontier performance: An application to Chinese province-level R&D," *Scientometrics*, vol. 82, no. 1, pp. 165–173, Jan. 2010.
[20] E. Ggifell-Tatjé and C. A. K. Lovell, "A DEA-based analysis of productivity change and intertemporal managerial performance," *Ann. Oper. Res.*, vol. 73, pp. 177–189, Oct. 1997.
[21] G. Abramo, T. Cicero, and C. A. D'Angelo, "A field-standardized application of DEA to national-scale research assessment of universities," *J. Informetrics*, vol. 5, no. 4, pp. 618–628, Oct. 2011.
[22] S. Malmquist, "Index numbers and indifference surfaces," *Trabajos de Estadistica*, vol. 4, pp. 209–232, 1953.
[23] D. W. Caves, L. R. Christensen, and W. E. Diewert, "The economic theory of index numbers and the measurement of input, output, and productivity," *Econometrica, J. Econ. Soc.*, vol. 50, pp. 1393–1414, Nov. 1982.
[24] D. D. Wang, "Performance assessment of major global cities by DEA and malmquist index analysis," *Comput., Environ. Urban Syst.*, vol. 77, Sep. 2019, Art. no. 101365.
[25] G. Egilmez and D. McAvoy, "Benchmarking road safety of U.S. states: A DEA-based Malmquist productivity index approach," *Accident Anal. Prevention*, vol. 53, pp. 55–64, Apr. 2013.
[26] H. N. Guo, "Evaluation of universities directly under the ministry of education scientific research efficiency," Ph.D. dissertation, Jiangsu Univ. Sci. Technol., Zhenjiang, China, 2012.
[27] X. S. Zhao, "Research on efficiency evaluation of scientific and technological innovation in universities of Shandong province," Ph.D. dissertation, Shandong Univ., Jinan, China, 2016.
[28] L. P. Qiu, "Research on the comprehensive evaluation of scientific research performance in higher agricultural universities," Ph.D. dissertation, Shenyang Agricult. Univ., Shenyang, China, 2017.
[29] T. Li, "Evaluation and research on input and output efficiency of scientific research in Chinese and American public universities," Ph.D. dissertation, Huazhong Agricult. Univ., Wuhan, China, 2018.
[30] A. T. Flegg, D. O. Allen, K. Field, and T. W. Thurlow, "Measuring the efficiency and productivity of British universities: An application of DEA and the Malmquist approach," Dept. Econ., Univ. West England, Bristol, U.K., Series Discussion Papers 304, 2003, pp. 1–41.
[31] M. Rahimian and M. Soltanifar, "An application of DEA based Malmquist productivity index in university performance analysis," *Manage. Sci. Lett.*, vol. 4, no. 1, pp. 337–344, Jan. 2013.
[32] J. Hicks, "The assumption of constant returns to scale," *Cambridge J. Econ.*, vol. 13, pp. 9–17, Mar. 1989.
[33] R. W. Jones, "Variable returns to scale in general equilibrium theory," *Int. Econ. Rev.*, vol. 9, pp. 261–272, Oct. 1968.
[34] K. Tone, "Malmquist production index, efficiency change over time," in *Handbook on Data Envelopment Analysis*, W. W. Cooper, L. M. Seiford, and J. Zhu, Eds. Dordrecht, The Netherlands: Kluwer Academic, 2004, pp. 203–227.
[35] Y. Q. Li, D. G. Yu, and J. F. Song, "Analysis of the status and influencing factors for patents output in colleges and universities in China," *Higher Agricult. Educ.*, vol. 3, pp. 39–42, Mar. 2007.
[36] A. Ashrafi, A. B. Jaafar, L. Lee, and M. R. Bakar, "An enhanced Russell measure of super-efficiency for ranking efficient units in data envelopment analysis," *Amer. J. Appl. Sci.*, vol. 8, p. 92, Jan. 2011.
[37] M. Nishimizu and J. M. Page, "Total factor productivity growth, technological progress and technical efficiency change: Dimensions of productivity change in Yugoslavia, 1965-78," *Econ. J.*, vol. 92, pp. 920–936, Dec. 1982.
[38] *Report on Advances in Materials Science and Engineering for 2006~2007*, Chin. Mater. Res. Soc., Beijing, China, 2007.
[39] A. D. Sutadian, N. Muttil, A. G. Yilmaz, and B. J. C. Perera, "Using the analytic hierarchy process to identify parameter weights for developing a water quality index," *Ecol. Indicators*, vol. 75, pp. 220–233, Apr. 2017.
[40] M. Esmaeili, "An enhanced Russell measure in DEA with interval data," *Appl. Math. Comput.*, vol. 219, no. 4, pp. 1589–1593, Nov. 2012.
[41] N. Aghayi, M. Tavana, and B. Maleki, "A Malmquist productivity index with the directional distance function and uncertain data," *Scientia Iranica*, vol. 26, pp. 3819–3834, Nov./Dec. 2019.

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