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# The Scientific and Technological Innovation Performance of Chinese World-Class Universities and Its Influencing Factors

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**ABSTRACT** This paper explores the scientific & technological innovation performance of world-class universities in China from 2014 to 2019, based on the super-efficiency DEA model and Malmquist index. Then we provide a novel five-dimensional analysis framework to research influencing factors of their S&T innovation efficiency with the Tobit-DEA model. The results show that 36.6% of the sample universities are DEA efficient, and their efficiency varies according to their type and location. Besides, the technical efficiency index of universities is relatively high and the total factor productivity is volatile, which are reflected in the ability of transforming scientific research achievements into practical productivity. From the perspective of dynamic analysis, the sample universities expand slowly in the frontier of S&T innovation efficiency. In addition, the S&T innovation performance is highly related to the input quality and matching structure of scientific research elements, government relevance, and industry-academia-research collaboration level. Among these main factors, the high proportion of full-time teachers with senior titles, reasonable resource allocation structure and government support have significant positive impact, whereas the number of participants in international academic has negative impact.

**INDEX TERMS** Influencing factor, Malmquist index, scientific & technological innovation, super-efficient DEA model, world-class university.

## I. INTRODUCTION

Inovation is the source of development power and the strategic support for the construction of modern economic system. The scientific and technological (S&T) innovation development of research universities, especially the world-class research universities, as one of the key parts of national scientific research forces, determines a country's position in global S&T innovation and industrial competition to a great extent [1]. Like enterprises, S&T innovation in universities should not only focus on the output of achievements, but also fully consider the efficiency, so as to obtain higher output with limited resource input. The governments have invested a lot of funds, human and material resources in the process of supporting the construction of universities. Therefore, the construction of world-class universities has been institutionalized as a long-term policy of many countries, including developing countries such as China (e.g. [2]) and India (e.g. [3]), and developed countries such as Germany (e.g. [4]), France (e.g. [5]), Japan (e.g. [6]), Singapore (e.g. [7])and South Korea (e.g. [8]). At present, China's economy has entered a high-quality development stage, and must rely on S&T innovation to release more economic development potential [9]. In September 2017, the Ministry of Education, the Ministry of Finance and the National Development &Reform Commission of China issued the notice on publishing the list of world-class universities under construction of China and forty-two universities were selected. Subsequently, a series of ''world-class university'' construction policies were introduced, and the investment in relevant universities continued to be increased. According to the latest budget data of universities released by the Ministry of Education, the budget of 11 universities in 2020 exceeds 10 billion RMB, of which Tsinghua University has the largest amount of budget, with 30.921 billion RMB [10]. With more and more investment in world-class universities,

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the government and society pay more and more attention to the efficiency and benefit of funds. It is of great significance to formulate a scientific performance evaluation system and corresponding incentive-restraint mechanisms [11]. Compared with teaching activities, the performance evaluation of S&T innovation has more observable indicators, and it is also an important part of the performance evaluation of world-class universities [12].

The existing research literatures on world-class universities in China mainly focused on the field of education, which discussed the connotation of China's world-class universities' system, the construction of teaching staff and the mode of talent training [13], [14]. However, there were relatively few articles researching on the S&T innovation performance from the perspective of economics. This paper uses the combination of SE-DEA, Tobit-DEA and Malquist index to analyze the S&T innovation of Chinese world-class universities, and it is organized as follows. We first review recent literatures on the topic of universities' S&T innovation. Secondly, we describe our main research methods and data sources. Thirdly, we evaluate the S&T innovation performance of world-class universities. This empirical research section is divided into two parts. The first part is static analysis. According to super-efficient DEA model, we calculate the S&T innovation efficiency in universities and use the super-efficiency decomposition to measure the efficiency of decision-making units (DMUs) in the frontier of data envelopment and analyze the heterogeneity of disciplines. The second part is dynamic analysis. We calculate the annual Malmquist index and its decompositions of S&T innovation performance of world-class universities from 2014 to 2019. Fourthly, we construct a five-dimensional theoretical framework to explore the factors influencing the S&T innovation performance. Finally, we conclude with results and implications.

## II. LITERATURE REVIEW

### A. S&T INNOVATION OF WORLD-CLASS UNIVERSITIES

In recent decades, researchers have fully discussed on the definition, characteristics, evaluation criteria, and international ranking of world-class universities [15], [16]. From the perspective of innovation system, S&T innovation of research-oriented universities refers to the whole process of promoting economic growth and social development by taking universities' scientific research personnel as the main body, integrating the funds and information resources from enterprises, governments and other institutions to create scientific knowledge and develop related technologies, and realizing the commercialization and industrialization of patent technologies and other S&T achievements through the technology market transactions, university S&T parks and other channels [17]–[19].

The S&T innovation activity in universities is a complex system with multiple inputs and outputs. There are many "products" that are difficult to be quantified accurately, and the quality of "products" lacks a unified standard [20]. Therefore, the benefit evaluation methods commonly used in general production systems or enterprises, such as the rate of return on investment method, present value comparison method and payback period method, are not suitable for the measurement of scientific research efficiency in universities. Faced with the failure of traditional methods, some scholars tried to use stochastic boundary analysis (SFA). As a parameter statistical method, SFA needs to construct a research production function and estimate the parameters on the frontier before it is used. In this process, the rationality of constructor has a great influence on the results, and the parameter estimation results will be different based on different assumptions. In addition, SFA is often used to deal with the case of only one output. For multi input and multi output system, the calculation process is very complex. With the development of evaluation theory and method, data envelopment analysis (DEA) provides a new way to solve this problem. The evaluation principles of DEA and SFA are similar, but as a nonparametric method, DEA does not need to determine the functional relationship between input and output in advance and estimate parameters, and its input-output index does not need dimensionless treatment. This series of advantages make DEA especially suitable for evaluating the relative efficiency of multi input and multi output complex systems, such as university scientific research system [21], [22]. With the development of efficiency evaluation researches, scholars tried to improve the original DEA model to make the evaluation process more in line with the characteristics of university scientific research systems. The original DEA model can only classify the target universities' efficiency into two or three categories, and has no ranking function; moreover, the classification evaluation results contain a large number of "pseudo effective units" [23], [24]. Therefore, scholars tried to increase the discrimination of DEA evaluation results, and the main improved model was super-efficiency DEA model [25], [26].

In view of the research trend and the characteristics of university scientific research activities, this paper chooses the improved super-efficient DEA model to meet the accuracy and value preference of university S&T innovation performance evaluation. It can carry out more in-depth evaluation and control operation for multiple effective DMUs.

As for the performance evaluation system of S&T innovation, scholars usually took the achievements of scientific researches and their contribution to social economy as the standard, especially attaching importance to scientific research achievements [27]–[29]. Throughout the relevant academic literature, the UK University Research Evaluation System (RAE) [30] and the annual evaluation report of "American Best Research University" are the two most influential evaluation systems [31], [32].

### B. INFLUENCING FACTORS

Compared with the evidence on research of S&T innovation performance in universities, the research on its influencing factors is relatively less [33]. On the one hand, due to the availability of data and other reasons, the evaluation index system is relatively simple. It values the scientific research quantity indicators such as the number of papers published, instead of paying attention to the scientific research quality indicators, such as citation rate, and more importantly, lacks the social and economic impact indicators of S&T innovation achievements [34]–[36]. On the other hand, most studies analyze the influencing factors of scientific research output from the perspective of individual scholars [37]. The analysis focusing on the institutional level is still in the exploratory stage, and the explanatory variables selected by different literatures vary greatly, including the level of regional economic development, geographical location, scale of universities, history of running schools, funding and discipline structure, and there is no relatively unified theoretical interpretation framework [38]–[40]. "World-class" construction is a long-term project. If there is no improvement of scientific research efficiency, only relying on high-intensity investment driving, it will not be sustainable. Therefore, it is of great theoretical and practical significance to use a more scientific method to measure the change trend and influencing factors of S&T innovation efficiency of world-class research universities in China. In view of this, this paper has attempted to improve the research work from the following aspects: (1) take the input-output efficiency of S&T innovation as the basic analysis method, build a performance evaluation index system that highlights the quality of scientific research output and the economic and social benefits of S&T innovation achievements; (2) evaluate the S&T innovation performance of the world-class universities of China by the super-efficient DEA model and Malmquist index evaluation method from both static and dynamic perspectives; (3) construct a five dimensional influencing factors method, and use Tobit-DEA model to make an empirical analysis of the influencing factors of S&T innovation in universities.

## III. METHODOLOGY

### A. RESEARCH METHODS

#### 1) SUPER-EFFICIENT DEA MODEL

Data envelopment analysis (DEA) can evaluate the relative effectiveness of each DMU. The basic models are $C^2R$ model and $BC^2$ model. The $C^2R$ model assumes that the same type of DMUs can increase output in equal proportion by increasing input, and the comprehensive efficiency (TE) is obtained, which reflects the ability of DMUs to achieve maximum output under given input [41].

Suppose there are n $DMU_j$s, each $DMU_j$ with m $x_{ij}(i = 1, \ldots, m, j = 1, \ldots, n, x_{ij} \geq 0)$ inputs and s $y_{rj}(r = 1, \ldots, s, j = 1, \ldots, n, y_{rj} \geq 0)$ outputs. $v_i$ and $u_r$ as weight coefficients, $v_i$ measures the type $i$ input, and $u_r$ measures the type $r$ output. The $C^2R$ model is:

$$Max\ h_{j0} = \frac{\sum_{r=1}^{s} u_r y_{rj_0}}{\sum_{i=1}^{m} v_i x_{ij_0}} \quad s.t.\ h_j = \frac{\sum_{r=1}^{s} u_r y_{rj_0}}{\sum_{i=1}^{m} v_i x_{ij_0}} \leq 1 \tag{1}$$

The solution satisfies $\sum_{r=1}^{s} u_r y_{rj_0} = 1$, which means under this circumstance that weighted sum of inputs is 1 to find the maximum of outputs weighted sum. The $BC^2$ model is obtained by adding hypothesis $\sum_{j=1}^{n} \lambda_j = 1$ on the $C^2R$ model, which separates scale efficiency (SE) from pure technical efficiency (PE) of DMUs. By dividing the total efficiency (TE) by its pure technical efficiency (PE), the capacity of each DMU to produce at the best scale under the same production conditions and management level is obtained, which is called scale efficiency (SE). The relationship among them can be expressed as TE = SE × PE.

However, $C^2R$ and $BC^2$ models often get multiple DEA relative efficiency values of 1, which can't be directly compared [42]. Therefore, this paper has adopted the super-efficient DEA model, and introduced slack variable $Z^-$ and residual variable $Z^+$ to allow the calculation results to be greater than 1. According to the duality theory of linear programming, Equation (1) is transformed into the mathematical expression of SE-DEA model [43]:

$$SE = \begin{cases} \min\left[\theta - \varepsilon\left(e^T z^- + e^T z^+\right)\right] \\ \sum_{j=1, j\neq j_0}^{n} \lambda_j x_{ij} + z^- \leq \theta_{j_0} x_{ij_0} \\ \sum_{j=1, j\neq j_0}^{n} \lambda_j x_{ij} - z^+ \geq y_{rj_0} \\ \sum_{j=1}^{n} \lambda_j = 1 \\ \lambda_j \geq 0, \quad j = 1, 2, \ldots, n, j \neq j_0 \\ z^+ \geq 0, z^- \geq 0 \end{cases} \tag{2}$$

$\theta \geq 1$ indicates that the DMU is effective DEA, and can be further sorted and compared; $\theta < 1$ indicates that the DMU is ineffective DEA. At this time, we can find the reason of DMU ineffective by observing whether the pure technical super-efficiency value and scale super-efficiency value are greater than 1.

#### 2) MALMQUIST INDEX

Because the frontier of each DMU is different every year, the efficiency value calculated by super-efficiency DEA model alone is not comparable among years. In order to evaluate the S&T innovation performance of universities, this paper not only needs horizontal static comparison within the world-class universities, but also needs vertical dynamic comparison among different years. Therefore, we combine the super-efficiency DEA model with Malmquist index to get more accurate efficiency growth value [44]. If the calculated Malmquist value is greater than 1, it indicates that the total factor productivity (TFP) is increasing from t period to $t+1$ period, that is, the level of comprehensive productivity is improved. If it is less than 1, it indicates that the TFP is declining. When a certain change ratio of the index is greater than 1, it indicates that it is the cause of the productivity increase. Otherwise, it is the cause of the productivity decrease.

$$\begin{aligned} M_0 &= \left(x^{t+1}, y^{t+1}, x^t, y^t\right) \\ &= \left[\frac{D_0^t\left(x^{t+1}, y^{t+1}\right)}{D_0^t\left(x^t, y^t\right)} \times \frac{D_0^{t+1}\left(x^{t+1}, y^{t+1}\right)}{D_0^{t+1}\left(x^t, y^t\right)}\right]^{1/2} \\ &= \frac{D_0^{t+1}\left(x^{t+1}, y^{t+1}\right)}{D_0^t\left(x^t, y^t\right)} \\ &\quad \times \left[\frac{D_0^t\left(x^{t+1}, y^{t+1}\right)}{D_0^{t+1}\left(x^{t+1}, y^{t+1}\right)} \times \frac{D_0^t\left(x^t, y^t\right)}{D_0^{t+1}\left(x^t, y^t\right)}\right] \\ &= EFFCH \times TECH \end{aligned} \quad (3)$$

Equation (3) gives the decomposition of Malmquist productivity index, which can be divided into efficiency change (EFFCH) and technology change (TECH) on the whole. EFFCH measures the contribution of technical efficiency change of productivity from $t$ period to $t+1$ period, and TECH mainly reflects the contribution of production frontier movement to productivity change, which indicates the technological progress or innovation. Furthermore, EFFCH can be divided into pure technical efficiency change (PEFFCH) and scale efficiency change (SEFFCH). PEFFCH is the change of technical efficiency under the assumption of variable returns to scale. The relationship among them can be expressed as ML = EFFCH × TECH = PEFFCH × SEFFCH × TECH [45].

### B. DATA SOURCES AND INDICATORS SELECTION

Nowadays there is no unified standard for the construction of S&T innovation performance index system in universities [46]. Generally speaking, the selection of evaluation indicators should be combined with the actual situation, and can reflect the specific situation of scientific research input and output. On the basis of the existing research, combined with the characteristics of S&T research input and output in Chinese universities, this paper has constructed the performance evaluation indicator system as shown in Table 1. Among the 42 research objects, the relevant data of National University of Defense Technology could not be acquired because of its special identity, the supreme military academy of China. Therefore, the DMUs analyzed in this paper are the other 41 world-class universities and the data are selected from the Statistical Report of Chinese College-run Industries, the Compilation of Scientific and Technological Statistics of Universities, the Education Statistics Yearbook of China, the Urban Statistics Yearbook of China and the field surveys conducted by our research team.

#### 1) INPUT INDICATORS SYSTEM

The input indicator system includes two second level of indicators, namely "human resources" and "scientific research funding", and three third levels of indicators, namely "the equivalent number of converted full-time personnel", "the internal expenditure on research funds" and "the number of S&T subjects obtained in the report year".

**TABLE 1. Performance evaluation indicator system of S&T innovation.**

| First level | Second level | Third level | Indicator unit |
|---|---|---|---|
| Input | Human resources | the equivalent number of converted full-time personnel | $X_1$/person |
| | Scientific research funding | the internal expenditure on research funds | $X_2$/ten thousand RMB |
| | | the number of S&T subjects | $X_3$/piece |
| Output | Basic innovation | the number of papers | $Y_1$/piece |
| | | the number of citations | $Y_2$/piece |
| | Application innovation | the number of patent authorizations | $Y_3$/piece |
| | | the national award for S&T achievements | $Y_4$/piece |
| | Experiment and development innovation | income from technology transfer, patent sale and school-run industries | $Y_5$/ten thousand RMB |

#### 2) OUTPUT INDICATORS SYSTEM

In the output indicator system, this paper uses the idea of "innovation value chain" for reference [47], [48], and divides it into three second level of indicators, "university S&T basic innovation", "university S&T application innovation" and "university S&T experiment and development innovation". In the basic innovation stage, the output of innovation activities is knowledge output, so it is measured by the number of published scientific research papers, that is, the total number of papers and the number of citations in Essential Science Indicator (ESI). Since ESI mainly includes papers published in international journals, and most of them are science and engineering subjects, this study selects the paper index of Chinese Social Science Citation Index (CSSCI) to reflect the Chinese research results of philosophy and social science. In the application innovation stage, the output of innovation activities are mainly inventions and patents, so it is measured by the number of patents authorized and the national award for S&T achievements. In the experiment and development innovation stage, the output of innovation activities is innovation income, so it is measured by the sum of the annual income from technology transfer, patent sale and school-run industries.

## IV. STATIC ANALYSIS OF S&T INNOVATION PERFORMANCE: DEA MEASUREMENT

This paper uses super-efficient DEA to analyze the data of the world-class universities from 2018 to 2019. The results are shown in Table 2.

**TABLE 2. Relative effectiveness of innovation performance of world-class universities from 2018-2019.**

| DMU | TE | PE | SE | Super-E | rank | DMU | TE | PE | SE | Super-E | rank |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Tsinghua University (THU) | 1 | 1 | 1 | 2.043 | 1 | Beijing Institute of Technology(BIT) | 0.865 | 0.907 | 0.958 | 0.869 | 22 |
| Renmin University of China(RUC) | 1 | 1 | 1 | 1.601 | 2 | Sun Yat-sen University(SYSU) | 0.856 | 0.912 | 0.940 | 0.857 | 23 |
| Peking University (PKU) | 1 | 1 | 1 | 1.411 | 3 | Harbin Institute of Technology(HIT) | 0.824 | 1 | 0.827 | 0.827 | 24 |
| Central University for Nationalities(MUC) | 1 | 1 | 1 | 1.294 | 4 | Yunnan University (YNU) | 0.821 | 0.947 | 0.895 | 0.822 | 25 |
| Xiamen University (XMU) | 1 | 1 | 1 | 1.276 | 5 | Sichuan University (SCU) | 0.816 | 1 | 0.818 | 0.818 | 26 |
| Chinese Marine University(OUC) | 1 | 1 | 1 | 1.163 | 6 | Dalian University of Technology(DUT) | 0.793 | 0.858 | 0.927 | 0.796 | 27 |
| Southeast University (SEU) | 1 | 1 | 1 | 1.117 | 7 | University of S&T of China(USTC) | 0.786 | 0.823 | 0.957 | 0.787 | 28 |
| Nanjing University (NJU) | 1 | 1 | 1 | 1.115 | 8 | Xi'an Jiaotong University(XJTU) | 0.774 | 0.779 | 0.998 | 0.778 | 29 |
| Nankai University (NKU) | 1 | 1 | 1 | 1.109 | 9 | Fudan University (FDU) | 0.705 | 0.874 | 0.806 | 0.707 | 30 |
| Lanzhou University (LZU) | 1 | 1 | 1 | 1.078 | 10 | University of Electronic S&T(UESTC) | 0.662 | 0.681 | 0.981 | 0.668 | 31 |
| China Agricultural University(CAU) | 1 | 1 | 1 | 1.079 | 11 | Xinjiang University (XJU) | 0.652 | 0.862 | 0.745 | 0.651 | 32 |
| Central South University(CSU) | 1 | 1 | 1 | 1.065 | 12 | South China University of Technology(SCUT) | 0.634 | 0.761 | 0.836 | 0.636 | 33 |
| Northwest A&F University(NWAFU) | 1 | 1 | 1 | 1.025 | 13 | Tianjin University (TJU) | 0.629 | 0.783 | 0.801 | 0.628 | 34 |
| Beijing University of Aeronautics and Astronautics (BUAA) | 1 | 1 | 1 | 1.019 | 14 | Zhengzhou University(ZZU) | 0.618 | 0.804 | 0.683 | 0.614 | 35 |
| Chongqing University (CQU) | 1 | 1 | 1 | 1.004 | 15 | Huazhong University of S&T(HUST) | 0.612 | 0.816 | 0.744 | 0.611 | 36 |
| Zhejiang University (ZJU) | 0.995 | 1 | 0.995 | 0.995 | 16 | Tongji University (TJiU) | 0.605 | 0.831 | 0.728 | 0.604 | 37 |
| WuHan University (WHU) | 0.941 | 0.984 | 0.958 | 0.947 | 17 | East China Normal University(ECNU) | 0.463 | 0.471 | 0.972 | 0.467 | 38 |
| Beijing Normal University (BNU) | 0.916 | 1 | 0.916 | 0.916 | 18 | Jilin University (JLU) | 0.412 | 0.533 | 0.781 | 0.416 | 39 |
| Northeastern University(NEU) | 0.903 | 0.950 | 0.953 | 0.905 | 19 | Hunan University (HNU) | 0.397 | 0.417 | 0.963 | 0.399 | 40 |
| Shanghai Jiaotong University(SJTU) | 0.879 | 1 | 0.890 | 0.890 | 20 | Northwestern Polytechnical University(NWPU) | 0.294 | 0.391 | 0.721 | 0.292 | 41 |
| Shandong University (SDU) | 0.874 | 0.975 | 0.898 | 0.873 | 21 | | | | | | |

### *A. COMPREHENSIVE EFFICIENCY (TE) ANALYSIS*

In Table 2, there are 15 universities have achieved DEA efficiency, accounting for 36.6% of the total. This shows that, the operation of world-class universities' S&T innovation in China is far from satisfactory on the whole.

Among the 26 ineffective DEA DMUs, there are not only traditional universities characterized by science and engineering, such as Harbin Institute of Technology, University of S&T of China, Shanghai Jiaotong University, but also comprehensive universities with a long history, such as Shandong University and Zhejiang University. Besides, among the 14 DEA effective DMUs, universities with science and engineering expertise, as well as the comprehensive universities are both included.

To evaluate whether the comprehensive efficiency (TE) of a DMU is effective, we use the pure technical efficiency (PE) and scale efficiency (SE). According to Table 2, the change directions of SE and TE of DMUs are almost the same. It can be inferred that the ineffective DEA of universities innovation performances are mainly attributed to their SE inefficiency.

Furthermore, we have analyzed the efficiency of S&T innovation from the types and regions of universities in Fig. 1. It is found that the average level of comprehensive universities is slightly higher than that of science and engineering. The average values of TE, PE and SE of comprehensive universities are 0.845, 0.902 and 0.930 respectively, while which of science and engineering universities are 0.773, 0.853 and 0.896. From the regional analysis, the overall level of the eastern region is the highest, and the three efficiency values are 0.875, 0.927 and 0.940 respectively. The three efficiency values of the western region are 0.779, 0.851 and 0.906, and that of the central region are 0.699, 0.797 and 0.861. In general, the gap in PE among the East, West and Center of China is greater than that of the SE.

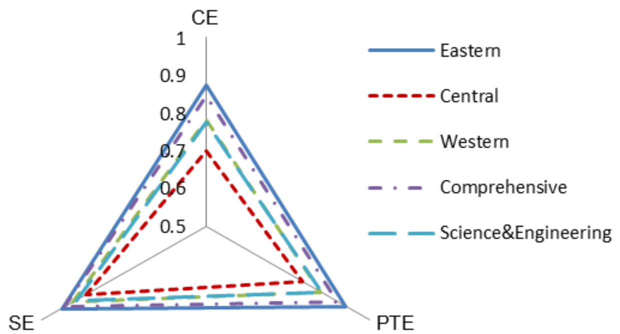


**FIGURE 1.** Performance of S&T innovation of world-class universities by types and regions.

### B. PURE TECHNICAL EFFICIENCY (PE) ANALYSIS

Pure technical efficiency (PE) refers to the maximum output of a DMU under the condition of given input combination. Table 2 shows that there are 20 research universities attaching the effective PE, accounting for 48.8% of the total sample, which is better than the TE and SE. Moreover, in the group of ineffective DEA DMUs, the values of PE are generally higher than that of the TE.

Table 2 also indicates that among these 21 DMUs with ineffective PE, more than half of them are famous universities with expertise in science and engineering, including Beijing Institute of Technology and University of S&T of China. The reason for this phenomenon may be that these universities once attached great importance to the discipline construction in social science, but now have transformed from single-disciplinary universities to multi-disciplinary universities, which has affected the allocation of academic resources.

### C. SCALE EFFICIENCY (SE) ANALYSIS

Scale efficiency (SE) examines whether the S&T innovation activities of research universities are in the optimal investment scale under the given technology level. Table 2 shows that there are 15 universities with effective SE, the same as TE. Table 3 shows the return to scale (RTS). Increasing returns to scale indicates that the DMUs should expand their scales and decreasing returns to scale indicates that the DMUs should reduce their scales. Among the universities

**TABLE 3.** Slack variable results of ineffective SE DMUs.

| DMU | $S_1^{-0}$ | $S_2^{-0}$ | $S_3^{-0}$ | RTS |
|---|---|---|---|---|
| ZJU | 0 | 0 | 0 | DEC |
| WHU | 0 | 0 | 0 | DEC |
| BNU | 0 | 0 | 1477 | INC |
| NEU | 0 | 63221 | 0 | INC |
| SJTU | 0 | 0 | 1986 | DEC |
| SDU | 1547 | 0 | 1081 | DEC |
| BIT | 0 | 90934 | 0 | DEC |
| SYSU | 1071 | 0 | 2014 | DEC |
| HIT | 0 | 75408 | 0 | DEC |
| YNU | 948 | 0 | 0 | DEC |
| SCU | 0 | 0 | 2120 | DEC |
| DUT | 0 | 0 | 0 | DEC |
| USTC | 0 | 0 | 0 | DEC |
| XJTU | 0 | 0 | 1494 | DEC |
| FDU | 0 | 0 | 36 | DEC |
| UESTC | 0 | 21385 | 0 | DEC |
| XJU | 0 | 9117 | 0 | DEC |
| SCUT | 0 | 0 | 1790 | INC |
| TJU | 0 | 71217 | 0 | DEC |
| ZZU | 0 | 0 | 722 | DEC |
| HUST | 0 | 0 | 133 | DEC |
| TJiU | 0 | 9578 | 0 | DEC |
| ECNU | 0 | 0 | 261 | DEC |
| JLU | 1178 | 0 | 72 | DEC |
| HNU | 0 | 0 | 0 | DEC |
| NWPU | 0 | 16687 | 0 | DEC |

with ineffective SE, 24 universities, including Fudan University and Shanghai Jiaotong University, are due to the decreasing returns to scale, while only Beijing Normal University, Northeastern University and South China University of Technology are due to the increasing returns to scale. This demonstrates that the investment of most world-class universities in China is effective. The emergence of these increasing and decreasing universities does not show a certain degree of regularity. There are not only comprehensive universities, but also universities traditionally based on the development of science and engineering.

This paper has further explored the reasons for the ineffective SE of these sample universities from the perspective of slack variable and residual variable in Table 3 and Table 4. The value of slack variable shows that compared with efficient DEA DMUs, the number of input elements of the ineffective universities should be reduced (or increased) under the condition of keeping output unchanged [49]. $S_1^{-0}$, $S_2^{-0}$, $S_3^{-0}$ correspond to the quantity that should be reduced of the input elements $X_1$, $X_2$, and $X_3$ respectively. Accordingly, under the condition of keeping input unchanged, the residual variables $T_1^{+0}$, $T_2^{+0}$, $T_3^{+0}$, $T_4^{+0}$, $T_5^{+0}$ correspond to the quantity that should be increased of the output elements $Y_1$, $Y_2$, $Y_3$, $Y_4$, and $Y_5$ respectively. Only for the three universities with increasing returns to scale, Beijing Normal University, Northeastern University and South China University of Technology, $S_1^{-0}$, $S_2^{-0}$, $S_3^{-0}$ correspond to the quantity that should be increased of input elements.

It can be found from Table 3 that $S_1^{-0}$ is not equal to zero in 4 universities, and $S_2^{-0}$ is not equal to zero in 8 universities, and $S_3^{-0}$ is not zero in 12 universities. Reducing or increasing the input of indicators corresponding to these slack variables can effectively improve the SE of these universities. In addition, there are 5 universities, including Zhejiang University, Wuhan University, Dalian University of Technology, University of S&T of China, and Hunan University, having all the three slack variables zero, so the main reason of their SE ineffective is not that they have too much inputs, but that their outputs are too little compared with the given inputs.

**TABLE 4.** Residual variable results of ineffective SE DMUs.

| DMU | $T_1^{+0}$ | $T_2^{+0}$ | $T_3^{+0}$ | $T_4^{+0}$ | $T_5^{+0}$ |
|---|---|---|---|---|---|
| ZJU | 0 | 11.57 | 37.49 | 0 | 0 |
| WHU | 0 | 0 | 0 | 0 | 4057.13 |
| BNU | 0 | 0 | 1.08 | 0 | 364.39 |
| NEU | 0 | 0 | 0 | 0 | 443.67 |
| SJTU | 0 | 0 | 77.04 | 7.52 | 0 |
| SDU | 0 | 0 | 0 | 2.63 | 0 |
| BIT | 0 | 0 | 0 | 0 | 0 |
| SYSU | 0 | 0 | 32.64 | 5.65 | 3272.32 |
| HIT | 0 | 0 | 0 | 0 | 805.86 |
| YNU | 0 | 0 | 21.00 | 4.81 | 0 |
| SCU | 0 | 0 | 0 | 4.53 | 4292.58 |
| DUT | 0 | 6.63 | 5.54 | 0 | 318.46 |
| USTC | 0 | 0 | 8.79 | 0 | 559.87 |
| XJTU | 0 | 5.74 | 4.59 | 0 | 0 |
| FDU | 0 | 0 | 20.61 | 0 | 3017.05 |
| UESTC | 0 | 0 | 0 | 1.76 | 4242.34 |
| XJU | 0 | 0 | 7.89 | 0 | 672.56 |
| SCUT | 0 | 4.01 | 12.15 | 0 | 0 |
| TJU | 0 | 0.73 | 0 | 0 | 437.89 |
| ZZU | 0 | 0 | 0 | 0 | 689.36 |
| HUST | 0 | 0 | 0 | 0 | 3081.01 |
| TJiU | 0 | 0 | 0 | 0 | 949.28 |
| ECNU | 0 | 0 | 0 | 0 | 875.46 |
| JLU | 0 | 0 | 0 | 5.49 | 3583.18 |
| HNU | 0 | 0 | 0 | 0 | 1401.53 |
| NWPU | 0 | 0 | 0 | 0 | 3288.26 |

Table 4 illustrates the reasons why the SE of these sample universities is ineffective from the perspective of outputs. On the whole, among the five output indicators, the sum of annual actual income of technology transfer and income increase in school-run industries ($Y_5$) is the biggest factor affecting their ineffectiveness, because 19 out of 26 DMUs are greater than 0 in this indicator. There are 11 universities whose residual variables of the number of patents authorizations ($Y_3$) are greater than 0, and 7 universities whose residual variable of the national award for S&T achievements ($Y_4$) are greater than 0, and 5 universities whose residual variable of the number of CNS publications ($Y_2$) are greater than 0. All the DMUs have achieved scale efficiency in $Y_1$ index. Combined with the situation of $Y_5$ and $Y_3$, we can conclude that the ability to transform scientific research achievements into practical productivity is the main factor affecting the S&T innovation performances of research universities.

## V. DYNAMIC ANALYSIS OF S&T INNOVATION PERFORMANCE: MALMQUIST INDEX

The frontier of each DMU is different every year, so the efficiency value calculated by super-efficiency DEA model alone is not comparable among years. In order to evaluate the S&T innovation performance of world-class universities in China, this paper not only needs horizontal static comparison, but also needs vertical dynamic comparison to analyze the development of sample universities' S&T innovation efficiency before and after the list publication. Therefore, we have chosen Malmquist index, the most widely used model in dynamic performance evaluation, combined with super-efficiency DEA to get more accurate efficiency growth value [50]. We have selected the data from 2014 to 2019 to calculate the *ML* index, *EFFCH* index and *TECH* index in Table 5 and demonstrated the annual Malmquist index changes of S&T innovation performance in Fig. 2. The index system selected is consistent with the static analysis to make the research results comparable and consistent.

**TABLE 5.** Annual malmquist index and its decompositions of S&T innovation performance of world-class universities in 2014-2019.

| Year | ML | EFFCH | TECH | PEFFCH | SEFFCH |
|---|---|---|---|---|---|
| 2014-2015 | 1.043 | 1.057 | 1.003 | 1.029 | 1.162 |
| 2015-2016 | 1.046 | 1.051 | 1.001 | 1.067 | 1.085 |
| 2016-2017 | 0.997 | 1.038 | 0.962 | 1.024 | 1.048 |
| 2017-2018 | 1.045 | 1.055 | 1.003 | 1.032 | 1.054 |
| 2018-2019 | 1.039 | 0.978 | 1.094 | 0.998 | 1.047 |
| Average value | 1.034 | 1.036 | 1.013 | 1.038 | 1.079 |

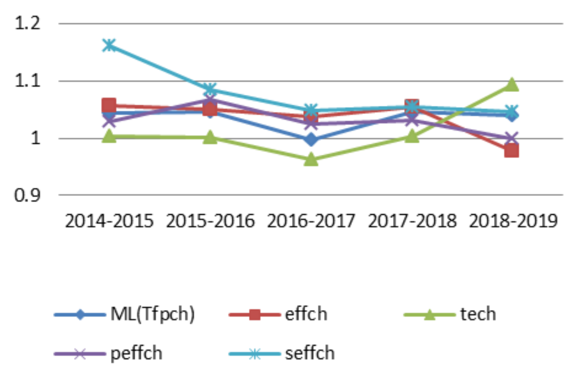


**FIGURE 2.** Change of annual malmquist index and its decompositions.

Combining with Table 5 and Fig. 2, we have found that the average value of ML of S&T innovation efficiency from 2014 to 2019 is 1.034, with an average annual growth rate of 3.4%, which indicates that the S&T innovation efficiency is growing. Then we have broken the results down and found that, firstly, the average value of technical efficiency change (EFFCH) is 1.036, which means due to the improvement of resource allocation and utilization efficiency, the average annual growth rate of production efficiency is 3.6%. Further analysis has indicated that the average value of pure technical efficiency (PEFFCH) is 1.038, and the annual change is not stable. The average value of scale efficiency (SEFFCH) is 1.079, which means the average annual production efficiency improvement caused by scale efficiency is 7.9%. However, the contribution of scale efficiency has been declining year by year, indicating that the marginal benefit of increasing input scale is decreasing, and the scale driven growth is unsustainable. Secondly, the average annual technology change (TECH) is 1.013, which means that the annual productivity increase caused by S&T innovation and its application improvement is 1.3%, far lower than the contribution of the improvement from management efficiency. And lastly, we have noticed that there is no obvious discontinuity in the year 2017 when the ''world-class university under construction of China'' list published.

The above analyses have proved that the sample universities expand slowly in the frontier of S&T innovation efficiency and need to further improve their original technology changes. In addition, the reason why since the policy was promulgated in 2017, the development of universities S&T innovation performance has not shown a significant growth may come from the other two aspects. First, among the 42 universities in the ''world-class universities'' list, there are 39 universities with ''985 project'' implemented in China, which have always been the top universities in China. Second, scientific projects, whether vertical or horizontal projects, need to go through a complex process from the beginning to the experimental development and then to the transformation of achievements, so the embodiment of policy effect has a certain lag. Yet it's worth noting that from 2018 to 2019, the technology change has been greatly improved.

## VI. EMPIRICAL ANALYSIS OF THE FACTORS INFLUENCING S&T INNOVATION PERFORMANCE

The purpose of evaluating the S&T innovation performance of world-class universities in China is not only to rank, but also to identify the factors that have significant impact on efficiency by using the big data platform [39], so as to provide more targeted decision-making reference for further development of universities' S&T innovation in China.

### A. ANALYSIS OF INFLUENCING FACTORS: FIVE-DIMENSIONAL INFLUENCING FACTORS METHOD

According to the knowledge production function and other related theories [51], based on the summary of relevant empirical research literature, this paper has proposed a five-dimension influencing factors method to explain the S&T innovation performance of universities. Specifically, it includes the input quality of scientific research elements, the matching structure of scientific research elements, the government relevance degree, the level of industry-academia-research collaboration, and the regional economic environment factors.

#### 1) INPUT QUALITY OF SCIENTIFIC RESEARCH ELEMENTS

The efficiency of knowledge production is highly dependent on the human capital accumulation of scientific researchers [52]. For developing countries, due to the international gap in science and technology, participating in international exchange and co-operation, and sharing knowledge spillover are undoubtedly ways of human capital appreciation, which can't be ignored [53], [54]. In this paper, we have selected ''the proportion of full-time teachers with senior titles'', ''the proportion of doctoral students in school'', and ''the number of participants in international academic conferences'' to characterize the human capital accumulation and value-added opportunities of university researchers.

#### 2) MATCHING STRUCTURE OF SCIENTIFIC RESEARCH ELEMENTS

In order to give full play to the professional human capital of scientific research personnel, researchers must be liberated from the tedious administrative tasks and financial affairs, which require the allocation of reasonable research auxiliary personnel. Therefore, we have chosen the proportion of scientific research auxiliary personnel as a representation of deepening division of labor and specialization [55]. Because the breakthrough of basic research is the foundation and source of knowledge innovation and it has strong spillover effect, we have selected the proportion of basic research funds to reflect the structure of the funding input factor [56]. The horizontal scientific research funds entrusted by enterprises and institutions have higher autonomy and flexibility in use, and their achievements are easier to be applied to the market [57], so we have used the proportion of research funds entrusted by enterprises and institutions as a structural factor affecting the scientific research efficiency of universities.

#### 3) GOVERNMENT RELEVANCE

The construction of research universities can't do without the financial support of the central and local governments in China. We have selected ''government funding'' to reflect the degree of interaction between research universities and the governments.

#### 4) INDUSTRY-ACADEMIA-RESEARCH COLLABORATION LEVEL

Industry-academia-research collaborative innovation is not only the basic way to improve the national industrial technology capability, but also an important driving force of S&T innovation in universities. We have selected ''the number of national technology research centers'' and ''performance scores of national university S&T parks'' to reflect the degree of collaborative development and mutual dependence among universities, industry and scientific research institutions.

#### 5) REGIONAL ECONOMIC ENVIRONMENT FACTORS

The economic development levels of regions where universities are located provide macro platforms for the input and operation of elements. The salary of researchers, living environment and the transformation and application of scientific and technological achievements all depend on the development of local economy and industry. Therefore, we have selected "per capita GDP" and "marketization degree", which reflect the level of economic development, as the regional environmental variables.

### B. DISCUSSION ON ECONOMETRIC MODELS AND RESULTS

In order to test the influencing factors of universities S&T innovation performance based on theoretical analysis, this paper use the two-stage Tobit-DEA model [58]. In the first stage, the super-efficiency DEA model is used to measure the innovation efficiency scores of each university; and the second stage is the regression of efficiency scores on various influencing factors. When the efficiency score is used as the explained variable of the regression model, it faces the data interception problem. The efficiency score is restricted explained variable because it has no value less than or equal to 0 and greater than 1. In this case, the estimation result of ordinary least squares (OLS) is biased and inconsistent. In order to avoid this phenomenon, the Tobit model is usually used to estimate the relation between restricted dependent variables and random independent variables. Since the 2014-2019 S&T innovation efficiency scores of world-class universities in China calculated in this paper are panel data, we adopt the Tobit model of panel data. Specifically, the paper uses the comprehensive efficiency (TE), pure technical efficiency (PE) and scale efficiency (SE) obtained from the super-efficiency DEA model in 2014-2019 as dependent variables, and the influencing factors in 2014-2019 as independent variables. The model is as follows:

$$Y_{it} = \alpha_0 + \beta_1 QAL_{it} + \beta_2 MsrC_{it} + \beta_3 GovC_{it} + \beta_4 IERC_{it} + \beta_5 RE_{it} + u_i + \varepsilon_{it} \quad (4)$$

Among them, $Y_{it}$ represents the SE-DEA value and its decomposition of sample universities; $QAL_{it}$ represents the input factors quality index; $MsrC_{it}$ represents the matching structure of scientific research elements index; $GovC_{it}$ represents the university and government relationship index; $IERC_{it}$ represents the industry-academia-research collaboration index; $RE_{it}$ represents the regional economic environment factor; $u_i$ represents the factors that are not changing with time and difficult to be observed; $\varepsilon_{it}$ represents the random interference factors. According to the results of BP test, F test and Hausman test, we have used the mixed OLS, fixed effect and random effect Tobit panel model, and displayed the specific regression results in Table 6.

Firstly, the regression coefficients of the proportion of full-time teachers with senior titles representing the human capital stock of scientific researchers are significantly positive in the three models. It reflects that high-level talents can significantly improve the S&T innovation of research universities. The accumulation of specialized knowledge and skills can not only improve its own output income, but also promote the increase of other input income and total scale income. Therefore, human capital is the decisive factor and permanent power of modern economic growth. The higher the quality of scientific research team is, especially the more high-level innovative talents, the higher the S&T innovation performance of universities will get. However, the proportion of doctoral students is only significant in scale efficiency. It can be seen that it is full-time teachers and their professional standards that can really improve the pure technical efficiency of scientific research and promote the connotative development of universities.

Except for the limited scale effect, the number of participants in international conferences has a significant negative impact on the S&T innovation of universities, which is consistent with the empirical research findings of relevant scholars by natural science data, that is, the international exchange and cooperation of universities do not have a positive impact on scientific research efficiency [59]. The economic cost of one-week academic conference participation in Europe or the United States is about 20-30 thousand RMB per person, almost equivalent to one year training fund for a doctoral student [60]. Consequently, considering the economic cost, the tedious administrative examination and approval, and the time spent by researchers, participating in international conferences may lose more than gain in many cases.

Secondly, the proportion of research auxiliary personnel has a supportive effect on the efficiency of scientific research, and it is significantly positive in all the three models, which shows that increasing the proportion of research auxiliary personnel can deepen the internal division of S&T innovation activities, free scientific researchers from complicated administrative affairs and make them concentrate on the professional academic field. The proportion of basic research funds can remarkably improve the comprehensive efficiency and pure technical efficiency of S&T innovation, but has no notable impact on scale efficiency, which not only reflects the leading and spillover functions of basic research, but also shows that it is more original than scale effect. The proportion of funds entrusted by enterprises and institutions only has a notable positive influence on scale efficiency, which indicates that the investment from the market is more inclined to expand the scale of disposable funds of universities, and has little effect on improving the efficiency of S&T innovation. And it also reflects that the academic quality of the entrusted projects needs to be improved.

Thirdly, the support of governments at all levels has a significant positive impact on the S&T innovation performance. The greater the government's support for a university, the more preferential policies such as capital investment, scientific research equipment and pilot base will flow to the university, and the output efficiency of its scientific research achievements will be greatly improved.

Fourthly, the level of industry-academia-research collaboration can significantly improve the universities S&T innovation in terms of comprehensive efficiency and pure technical efficiency. This shows that the more the national engineering/technology research center relying on the research university to be built and the higher the performance score of the university's science park, the closer the

**TABLE 6. Estimated results of the influencing factors of S&T innovation performance in world-class universities.**

| Dimension | Independent variable | TE Model1-RE | PE Model2-RE | SE Model3-FE |
|---|---|---|---|---|
| Input quality of scientific research elements | proportion of full-time teachers with senior titles | 0.2905** | 0.5797*** | 0.3558** |
| | | (0.314) | (0.0193) | (0.194) |
| | proportion of doctoral students in school | 0.893 | 0.0986 | 0.1633** |
| | | (0.772) | (0.057) | (0.546) |
| | number of participants in international academic conferences (Logarithm) | -0.0581* | -0.0325** | 0.1044** |
| | | (0.0259) | (0.159) | (0.121) |
| Matching structure of scientific research elements | proportion of research auxiliary personnel | 0.7891*** | 0.4205** | 0.4093*** |
| | proportion of basic research funds | (0.127) | (0.1088) | (0.211) |
| | | 0.347*** | 0.584*** | -0.0203 |
| | | (0.174) | (0.1422) | (0.0679) |
| | proportion of funds entrusted by enterprises and institutions | -0.0086 | -0.1287 | 0.1103** |
| | | (0.138) | (0.0682) | (0.0729) |
| Government relevance | relative support from the central government | 1.0163*** | 0.8628*** | 0.7834*** |
| | | (0.382) | (0.421) | (0.193) |
| | relative support from the local government | 0.763*** | 0.569*** | 0.677*** |
| | | (0.183) | (0.0162) | (0.0283) |
| Industry-academia-research collaboration level | number of national technology research centers | 0.1407* | 0.0324* | 0.1089 |
| | | (0.0456) | (0.173) | (0.0674) |
| | performance scores of national university S&T parks | 0.00522* | 0.1551* | 0.3011 |
| | | (0.166) | (0.1323) | (0.0672) |
| Regional economic environment factors | per capita GDP (Logarithm) | 0.0095 | 0.1023* | -0.0527 |
| | | (0.0382) | (0.0524) | (0.0340) |
| | marketization degree | -0.1787 | -0.4581 | -0.0420 |
| | | (0.0632) | (0.132) | (0.0193) |
| | Constant term | 0.347 | 0.0691 | -0.0793 |
| | | (0.521) | (0.407) | (0.332) |
| | Hausman test | 0.983 | 0.951 | 0.0584 |
| | R-squared | 0.269 | 0.271 | 0.501 |

Note: the standard error is in brackets. ***P<0.01, **P<0.05, *P<0.1. Random effects (RE) report $R^2$-overall, and fixed effects (FE) report $R^2$-whthin.

relationship between the university and enterprises. The circulation of knowledge can better promote the production and commercialization transfer of the university's R&D achievements, and ultimately significantly improve the overall performance of S&T innovation activities.

Fifthly, in the regional economic indicators, the per capita GDP has a significant positive impact on the pure technical efficiency, indicating that the high economic development can promote the resource allocation and management efficiency. However, the "marketization degree" has no significant impact on the S&T innovation performance. This conclusion is somewhat surprising. It may come from two aspects: One is that at present, the S&T innovation activities of universities in China still stay in knowledge production stage, not closely relating to the region development, and the extension of knowledge innovation to the practical business application field is not good enough. The other is that, due to the uneven distribution of demand and supply of innovative knowledge, many universities' research and innovation achievements are not directly transferred to local enterprises, but to other different regions. These phenomena may lead to the result of no significant correlation between the university scientific innovation and local marketization.

## VII. CONCLUSION

This paper has applied super-efficiency DEA model, Malmquist index and Tobit-DEA model to analyze the S&T innovation performances and their influencing factors of world-class universities in China from 2014 to 2019. Our results have demonstrated that the overall operation of S&T innovation activities is unsatisfactory and scientific research resources have not been fully and effectively utilized. The ability to transform scientific research achievements into practical productivity is the main factor affecting universities S&T innovation improvement. In the views of subject proportion structure, the research objects include comprehensive universities, universities mainly specialized in humanities and social sciences, universities focusing on science and engineering, and higher normal universities. Through data analysis, we find that the S&T innovation performances are uneven, and the rankings are also cross mixed. But overall, the performance level of comprehensive universities is slightly higher than that of science and engineering universities. In the views of regional development, the eastern region of China has the highest level, followed by the western region, and the central region is the lowest.

Although the efficiency of S&T innovation of sample universities is not high as a whole, it shows an upward trend. And this trend mainly comes from the improvement of scientific research management efficiency and scale adjustment. But it is deserved following with interesting that the technology changes of universities in 2018-2019 have been greatly enhanced.

The empirical analysis of S&T innovation performance influencing factors has affirmed that the influences of different factors on the efficiency and composition of S&T

innovation in universities have large divergences. Among them, the proportion of doctoral students in school and the proportion of enterprise entrusted funds only have significant impact on scale efficiency. The proportion of basic research funds and the industry academy research collaboration level only have notable effect on the comprehensive efficiency and pure technical efficiency of S&T innovation. The proportion of full-time teachers with senior professional titles, the proportion of research auxiliary personnel and the relative support from the central and local governments, which represent the stock of human capital and the depth of professional division, have dramatic influence on all the three indicators of S&T innovation performance of world-class universities in China.

Due to the limited ability, this paper also has some problems that need to be studied in the future. Firstly, this paper only considers the difference of indicators in the evaluation of S&T innovation efficiency, but does not reflect the value orientation. Therefore, the accuracy of the evaluation model could be improved by increasing the saving domain in the future research. Secondly, the model used in this paper is suitable for objective indicators and data, which limits its application scope to a certain extent. Typically, this problem can be more prominent in the research of universities efficiency due to the difficulty of data acquisition. Therefore, future research can explore the improvement of the model in multiple situations and expand its application scope.

In future research, we will further integrate DEA-based models, Malmquist index and five-dimension influencing factors method to expand the research scope and compare the S&T innovation performance level of universities in different economic development regions in China. Besides, we can try to explore the reason of efficiency differences between universities by using difference-in-difference regression method. Lastly, we will try to select data from different countries for comparison and discussion. For example, we can get the data from universities in the USA to compare the data with China, which is also a comparison between developed and developing countries. The integrated framework proposed in our research can be used for many objects, such as talent training efficiency, resource utilization efficiency, and cross-border integration efficiency. Therefore, this research plays a guiding role to some extent in analyzing other kinds of universities in other countries.

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