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Evaluating the Innovation Efficiency of Higher Education Institutions in Mainland China: A Two-stage Analysis with Time Lag Effects

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Abstract: The ability of higher education institutions (HEI) to innovate directly affects the overall scientific and technological strength and economic development speed of the region. Many studies have examined the innovation efficiency of HEIs, but more detailed studies are needed that address time lag effects and that apply the latest evaluation orientation. To this end, this paper focuses on higher education institutions in 31 provinces in mainland China and applies an improved two-stage Data Envelopment Analysis method to evaluate their innovation efficiency from 2014 to 2020. This study divides the innovation process of higher education institutions into two stages: applications for project funding (e.g., grant applications) and project research. The study considers how projects applied for in previous years contribute to the current year's scientific research results, and a semi-global production possibility set is constructed for dynamic measurements that are comparable across periods. There were three main study results. (1) The overall HEI innovation efficiency experienced a two-period growth process, growing from 0.7900 in 2014 to 0.8218 in 2017 in the first period, and further increasing to the highest level of 0.8473 in 2020 in the second period. (2) The efficiency of the project research stage was generally higher than the project application stage; innovative resources were used at a higher level of utilization during project research rather than project application. (3) The top five provinces in HEI innovation efficiency, represented by Beijing, also have a large number of top universities.

Keywords: Innovation efficiency; Higher education; Two-stage Data Envelopment Analysis; China

1 Introduction

Enhancing the ability to independently innovate is a major developmental goal of countries around the world. The key to independent innovation lies in having the appropriate talent, and the key to personnel talent development lies in education. Higher education institutions (HEIs) provide a crucial junction of science and technology (S&T) and innovative talents, and they often nurture original breakthroughs in basic research and cutting-edge technologies. The innovation efficiency of HEIs is an important symbol of a country's core competitiveness (Zhu et al., 2023). Meanwhile, innovation efficiency is also an internal driving force that enhances the nation's ability to innovate ability and promote the country's economic and social development (Fuentes et al., 2016).

With the rise of a new round of scientific and technological revolution, China has been paying increased attention to improving its independent innovation capability (Gong et al., 2022). In *the 12th Five-year Plan for National Economic and Social Development*, China proposed to enhance its independent innovation capabilities, by strengthening the innovation power of scientific research institutes and universities. This called for thoroughly implementing two major strategies: revitalizing China through science and education and strengthening the country through human resource development. China has continuously increased its investment and support to enhance the innovation ability of HEIs. The number of research and development (R&D) institutions in HEIs more than quadrupled from 3,936 in 2005 to 19,988 in 2020. Both R&D personnel and expenditures in HEIs also continued to grow. The full-time equivalents (FTEs) of R&D personnel increased by 24.23 thousand person-years annually between 2005 and 2020. Of these, the FTEs in basic research increased the fastest, contributing more than 50% of the growth in FTEs of R&D personnel. The same performance happened with S&T achievements. Scientific papers issued, S&T publications, and patents produced by HEIs also grew significantly. There has been a significant quantitative increase in both the innovation inputs and outputs of Chinese HEIs, reflecting the continuous improvement of HEI innovation abilities. However, the total amount only shows the growth in the scale of innovation, which is a relatively weak way to evaluate the real growth in the quality of HEI innovation from the perspective of input-output efficiency. In this context, it is important to identify HEIs' innovation efficiency and further explore the advantages and shortcomings of innovation.

Innovation efficiency is one of the three major types of HEI efficiency: teaching, innovation, and sustainability efficiency (Wang et al., 2019). Previous studies have extensively researched HEI innovation efficiency, and fall into two general types. The first type involves the study of the innovation efficiency of different disciplines and departments (Ma et al., 2021; Mirasol-Cavero et al., 2023); the second type investigates the overall innovation efficiency of HEIs. Studies on the disciplines and departments' innovation efficiency are often conducted within a HEI, while studies on the overall HEI innovation efficiency tend to compare analysis of different HEIs. More studies have focused on the second type of research. Studies have evaluated the innovation efficiency of HEIs in Australian, Greece, the United States, Europe, and other countries (Abbott and Doucouliagos, 2003; Katharaki and Katharakis, 2010; Lee et al., 2013; Klumpp, 2018). As China has strengthened its support for HEI innovation and has improved HEIs' innovation ability, studies on HEI innovation efficiency in China have become a research hotspot (Wu et al., 2020; Ma and Li, 2021; Ma et al., 2022). As noted above, overall HEI innovation efficiency studies generally fall into two categories: institution-based and region-based (Zhang et al., 2021; Zhao et al., 2022).

It is generally accepted that the HEI innovation process does not involve just a single input, nor can it be measured by a single output. The Data Envelopment Analysis (DEA) method can address multiple inputs and multiple outputs and is considered an effective method for evaluating the HEI innovation efficiency, and has been widely applied in the research field (Thanassoulis et al., 2011; de Witte and López-Torres, 2017; Wang, 2019; Navas et al., 2020; Zhao et al., 2022). The specific indicators of innovation outputs are represented by the number of research publications, such as scientific papers, monographs (Auranen and Nieminen, 2017; Agasisti et al., 2021), patents, and their influence (Avkiran and Rowlands, 2008; Chen et al., 2021). Output indicators are represented by researchers, projects and funding, and expenditure (Wang 2019; Xiong et al., 2020).

Previous studies have enriched the research field of HEI innovation efficiency from different focal points and perspectives. However, there are opportunities to expand the existing literature. First, measuring HEI innovation efficiency is mainly based on a single-stage process, and most studies have not opened the "black box" of the innovation process in HEIs. Second, the multi-stage HEI innovation analyses are frequently conducted based on research and transformation stages. In contrast, there few studies have analyzed how innovation achievements are obtained, and the process of utilizing innovation resources. Third, better assessments are needed about how evaluations match reality. For example, in recent years, an increasing number of Chinese HEIs have used project applications as an important indicator for evaluating faculty. In contrast, few studies have considered the projects actually undertaken when evaluating the efficiency of HEI's innovation.

To address the above needs, this paper evaluates the HEI innovation efficiency in mainland China from 2014 to 2020. An improved two-stage DEA model is adopted, focusing on HEIs in 31 provinces in mainland China. Specifically, this paper extends the existing literature in the following three ways. First, it reflects the real evaluation orientation of project application by opening the "black box" of HEI's innovation process. In this paper, the innovation process is divided into two stages: project application (that is, seeking financial support) and scientific research. This expands the research of HEI innovation from conception to idea formation to practical research and production of scientific research achievements. Second, this study considers the intertemporal impact of scientific research. The HEI innovation process does not yield immediate achievements, rather, it achieves cumulative effect over time. It is often likely that innovation achievements are supported by current year projects, and projects applied for successfully in previous years. Existing studies have considered the intertemporal impact of the projects to a certain extent, and this study further addresses this reality by considering different impacts of the projects on the research process in different periods. Third, this study constructs an intertemporal innovation efficiency measurement model with the project life cycle. When applying the DEA framework to measure innovation efficiency, changes in the production possibility set (PPS) of each period may lead to the incomparability of the efficiency levels when measured across periods. However, measurements under a global PPS change the efficiency values of the previous years, due to the addition of new year data. Given this, this study constructs a semi-global PPS with the projects' life cycle as the time span. This enables a comparison of the measured innovation efficiency values across periods, and avoids the change in efficiency values caused by updates in the data year.

The rest of this paper is organized as follows. Section 2 describes the study's conceptual framework. Section 3 presents the methodology used to evaluate the HEI innovation efficiency. Section 4 analysis the empirical results, and Section 5 concludes this study.

2 Conceptual framework

2.1 Innovation process of HEIs

When evaluating the level of an HEI's research function, it is widely accepted that workforce and funds are critical elements to produce research achievements. Scientific research is inseparable from financial support. In actual research, most funds are allocated in the form of projects and are frequently reflected in published paper acknowledgments. Recently, the evaluation of HEIs and their faculties in reality have emphasized the importance of research projects, which are considered an important source of research funding and an indicator of research capability. This stage is also the embodiment of a Resource-based View (Wernerfelt, 1984), which holds that heterogeneous resources are the source of durable competitive advantage and improved firm performance. Heterogeneous resources must satisfy four properties; they must be valuable, rare, difficult to imitate, and non-substitutable. Expanding this theory into the HEI innovation process, the proposal used for a project application must also meet these four properties if a grant is to be awarded. In general, only the projects that are funded are the main source of HEI's innovative achievements. Therefore, we construct a two-stage conceptual framework for the innovation process.

The project application is the first stage of HEIs' scientific and technological innovation. This stage is the gestation stage of the HEI innovation process, when researchers apply for projects based on their research ideas. The review process that follows is the first round of screening for innovative and feasible research points. At this stage, researchers apply for projects based on existing resources. We assume that all personnel are fully invested, and FEI faculty have the will and motivation to do the research. In the first stage, all the faculty with the scientific research capability and qualifications apply for research projects, including professors, lecturers, and tutors. In the meantime, financial support is inevitably provided to support the project application process. There are diverse funding needs and purposes, such as pre-experimentation tests and data purchases. Similarly, there may be different funding sources, such as the government, enterprises, and institutions, or other sponsorships. **Fig. 1** shows the specific project application stage process.

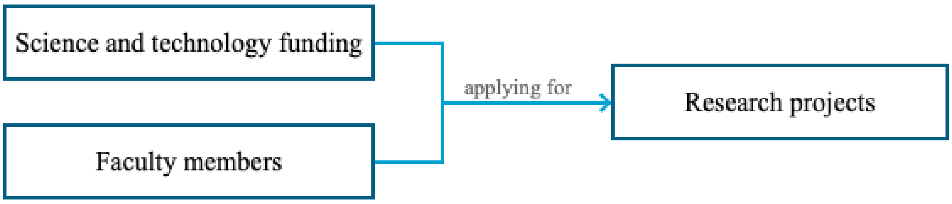


Fig. 1. The process of the project application stage

After successfully applying for the projects, the university's research process enters the second stage. In the second stage, researchers who have successfully applied for the projects conduct research using project funding and accomplish corresponding research achievements. There are three types of inputs in this stage: the project funding, the personnel involved in the project research, and project implementation. The funding can be traced back to its source and is associated with the explicit purpose of supporting the research on the corresponding topic. The number of researchers involved in this second stage is smaller than the previous stage because not all researchers are awarded projects.

Projects were selected as input indicators in this study, due to the consideration of the actual development situation and the research process. A growing number of Chinese HEIs consider the undertaking of a project to be a critical criterion for evaluating the faculty members' performance in their employment period. Some HEIs require national-level projects; others require provincial or ministerial-level projects. Moreover, when competing for professional titles, the number, level, and funding scale of the projects undertaken affect the score of competing researchers. From the perspective of the research process, personnel and funding inputs alone may not fully measure the innovation capability of HEIs.

Assume there are two HEIs, A and B, which have the same amount of personnel and funding input. A has a relatively small number of projects and more achievements compared to B. This may indicate that the overall scientific research strength of A is weaker than B, as there are fewer projects allocated to each faculty member in university A. This may indicate that each faculty member has access to fewer resources, such as funding support, influence, and voice in the related research fields. University B has a larger number of subjects, however, has fewer achievements, reflected in a low project utilization level and fewer average outputs from each project. This may indicate there are wasted resources. In addition to financial support, the projects also provide other resources for scientific research and innovation, such as academic exchanges, scholarly communications, and research cooperation. Therefore, this study also sets the number of projects as an evaluation criteria, in addition to funding and personnel input. **Fig. 2** shows the specific process involved in this research stage.

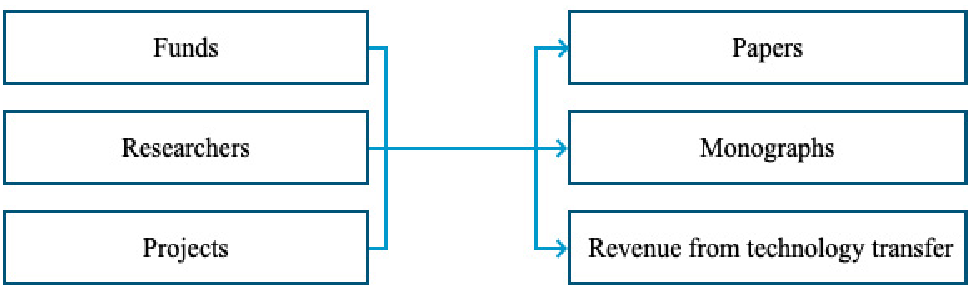


Fig. 2. The research stage process

Based on the analysis above, **Fig. 3** shows the innovation process of Chinese HEIs. The overall conceptual framework is grounded in the assumption that scientific research is supported by corresponding projects. The innovation capability of a university is reflected in the traditional indicators such as papers, monographs, and patents. Patents represent the ability to earn revenue through technology transfer; the innovation capability, funding support, and academic influence represented by research projects are also important pursuits with respect to HEIs' innovation. These are also crucial dimensions to measure the innovation efficiency of HEIs. This study assumes that university personnel want research project applications to be successful. Applying for projects consumes labor and resources, and is the first stage of the university's innovation process. Conducting the scientific research itself is referred to as the project research, with scientific achievements that include papers, monographs, and technology transfer revenue. This is the second stage of the university's innovation process. The research period of the projects may exceed one year. As such, some approved and funded research projects are approved in the current year, while others may have been approved in previous years.

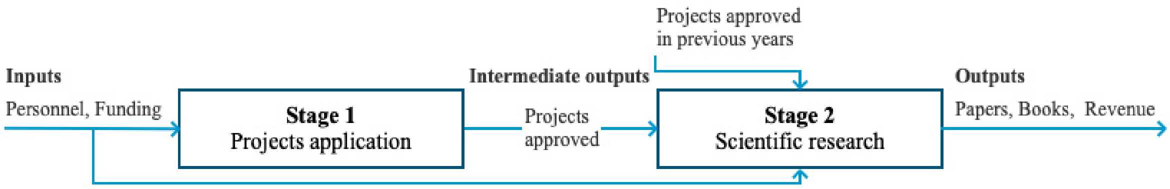


Fig. 3. The HEIs' overall innovation process

2.2 Variables and data collecting

According to the HEIs' overall innovation process, **Table 1** shows the input-output indicator system for evaluating the innovation efficiency of Chinese HEIs.

Table 1. The input-output indicator system for the innovation efficiency evaluation

Stages	Dimensions	Indicators	Units
Stage 1 (Application)	Inputs	Research and development personnel	persons
		Research funding	thousand yuan
	Outputs	Research projects	items
Stage 2(Research)	Inputs	Research projects	items
		Researchers engaged in projects	persons
		Expenditure on projects	thousand yuan
	Outputs	Academic papers	items
		Academic monographs	items
		Technology transfer revenue	thousand yuan

Stage 1 inputs include research and development (R&D) personnel and research funding. The output is research projects. Fig. 3 shows that the output is an input to the second stage. The other two inputs into the second stage (i.e., researchers engaged in projects and expenditure on projects), are partly shared with the inputs to the first stage. All the indicators in **Table 1** come from the *Compilation of Science and Technology Statistics of Higher Education Institutions* released by the Ministry of Education of the People's Republic of China.

Specifically, R&D personnel refers to faculty whose R&D activities account for more than 10% of their total teaching and scientific research time in the current year. R&D includes basic research, applied research, and experimental development. Research funding is defined as the funding directly used for research and development in the current year, funded by the government, enterprises, and other institutions. Research projects are undertaken by the teachers and researchers of the evaluated university, including projects supported by public and private funding. Technology transfer revenue refers to the remaining income generated by the technology holder's technology transfer or supply for use by buyers, excluding taxes and other losses during the transfer.

2.3 Characteristics of samples

This study focuses on Chinese HEIs. The geographical scope includes mainland China, and is conducted at the level of provinces. The study covered the time period 2014-2020. **Fig. 4** shows the average values of the inputs and outputs of the objects reflected at the provincial level.

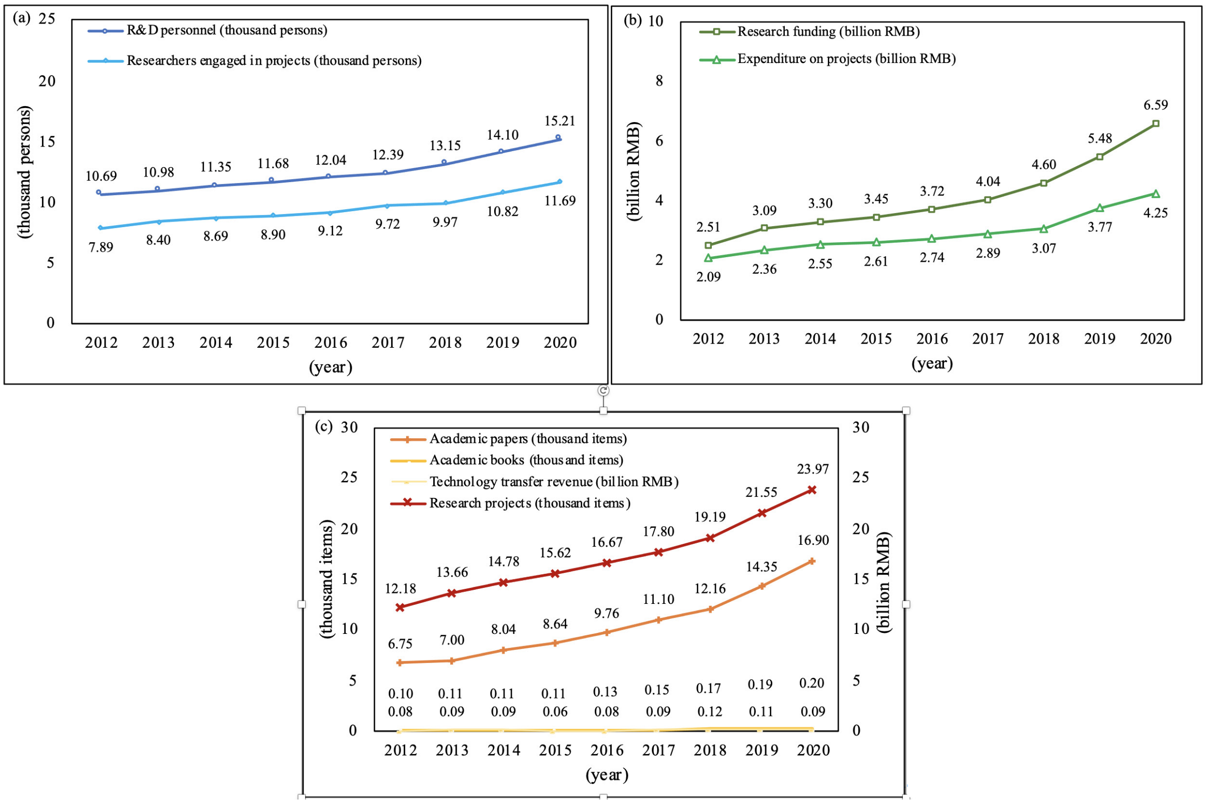


Fig. 4. The average values of (a) personnel inputs, (b) expenditure inputs, and (c) achievements in the innovation process of Chinese HEIs.

To comprehensively enhance the innovation capabilities of its higher education institutions, China launched the *Plan for Higher Education Institutions Innovation Capability Enhancement* in 2012. After that, the scale of R&D personnel in Chinese higher education institutions and R&D expenditures continued to increase. The average number of HEI R&D personnel in 31 provinces, autonomous regions, and municipalities in mainland China increased from 10,694 to 15,209 people in 2020, reflecting an increase of 42.22%. The increase in research funding from the government, enterprises, and institutions was even more significant. The average amount of research funds increased from 2.51 billion RMB in 2012 to 6.59 billion RMB in 2020, reflecting an average annual increase of 0.51 billion RMB.

The continued manpower and funding inputs have resulted in many scientific research achievements. The number of scientific research projects undertaken by HEIs increased every year, doubling from 12,181 in 2012 to 23,970 in 2020. In addition to the increase of the total quantity of projects, the number of projects per person (per capita R&D personnel) also increased in the nine year study period, from 1.14 to 1.58. Based on the support and funding of different research projects, scientific research achievements were also assessed, by examining by academic monographs, papers, and technology transfer revenue The growth in the number of papers was the most significant. The average number of papers published in international and national journals among the 31 provinces, autonomous regions, and municipalities more than doubled between 2012 and 2020. The number of academic monographs published each year also grew, which was a lower growth rate compared to the papers. Compared with the steady growth of the achievements above, the technology transfer revenue rose with fluctuations during 2012-2020, from 77.74 million RMB to 92.73 million RMB, peaking at 118.06 million RMB in 2018.

From a provincial perspective, R&D personnel and expenditures in Beijing ranked first around the country from 2012 to 2020; this was followed by Shanghai and Jiangsu province. Of these latter two regions, Shanghai had more R&D personnel, while Jiangsu exceeded Shanghai in terms of R&D expenditure. With respect to research projects and research achievements, Jiangsu province fully surpassed Shanghai after 2014, with the number of research projects, academic monographs, papers, and the amount of technology transfer revenue all ranking above Shanghai. However, Beijing also ranked first in the country in these variables. In contrast, HEIs in the northwest China were relatively weak with respect to research manpower and funding support. The northwestern provinces represented by Tibet and Qinghai were lowest in the country in terms of R&D personnel, R&D expenditures, and fewer research achievements.

3 Methodology

Data Envelopment Analysis (DEA) is frequently used to measure efficiency, and has been widely used to evaluate innovation efficiency in higher education institutions (Navas et al., 2020). Traditional DEA models mostly use radial models to measure efficiency, with inputs and outputs increasing or decreasing proportionally. However, the radial measure may not consider the slack in the inputs and outputs when measuring the efficiency. The efficiency may be overestimated when there is a non-zero slack in the optimal solution (Arbona et al., 2022). Therefore, the slacks-based measure (SBM) is used to evaluate the innovation efficiency of Chinese HEIs in this study.

3.1 Model of the two sub-stages

Assume there are n decision making units (DMUs) at time t ($t = 1, \ldots, T$). In this study, the DMUs are the provinces in mainland China. Using the conceptual framework in Section 2, we divide the innovation process of Chinese HEIs into two stages. In the first stage, each $DMU_j\left(j = 1, \ldots, n\right)$ consumes m inputs $x_{ij}\left(i = 1, \ldots, m;\ j = 1, \ldots, n\right)$ to produce k outputs $z_{lj}\left(r = 1, \ldots, k;\ j = 1, \ldots, n\right)$. The production possibility set (PPS) of stage 1 is described as $PPS^1 = \left\{\left(\boldsymbol{x}, \boldsymbol{z}\right) \middle| \boldsymbol{x}\ can\ produce\ \boldsymbol{z}\right\}$, where $\boldsymbol{x}$ and $\boldsymbol{z}$ are the input and output vectors in Stage 1. Some of the outputs in Stage 1 may be inputs into Stage 2; therefore, $\boldsymbol{z}_{lj}$ are also called intermediate outputs in the two-stage production process.

Subsequently, $DMU_j\left(j = 1, \ldots, n\right)$ consumes $\boldsymbol{z}_{lj}$ and produces q outputs $y_{pj}\left(p = 1, \ldots, q;\ j = 1, \ldots, n\right)$. As noted above, researchers who successfully apply for projects conduct the scientific research funded by the projects and achieve innovations. Therefore, Stage 2 has some of the same inputs as Stage 1. Similarly, the PPS of Stage 2 is described as $PPS^2 = \left\{\left(\alpha \boldsymbol{x}, \boldsymbol{z}, \boldsymbol{y}\right) \middle| \left(\alpha \boldsymbol{x}, \boldsymbol{z}\right)\ can\ produce\ \boldsymbol{y}\right\}$, where $\boldsymbol{z}$ is the input vector instead of the output vector in Stage 2; $\boldsymbol{\alpha x}$ is the shared inputs of Stage 1; and $\boldsymbol{y}$ is the output vector. Then, the model measuring innovation efficiency is defined based on the preliminaries and notations.

Stage 1 (project application):

$$\theta^1 = \min \frac{1 - \frac{1}{m}\sum_{i=1}^{m}\frac{s_i^{x,t}}{x_{io}^t}}{1 + \frac{1}{k}\sum_{l=1}^{k}\frac{s_l^{z,t}}{z_{lo}^t}}$$

$$\begin{aligned} s.t.\quad & \sum_{j=1}^{n}\lambda_j^{1,t}x_{ij}^t = x_{io}^t - s_i^{x,t} \\ & \sum_{j=1}^{n}\lambda_j^{1,t}z_{lj}^t = z_{lo}^t + s_l^{z,t} \\ & \sum_{j=1}^{n}\lambda_j^{1,t} = 1 \\ & s_i^{x,t},\ s_l^{z,t},\ \lambda_j^{1,t} \geq 0 \\ & i = 1, \ldots, m;\ l = 1, \ldots, k; \\ & j = 1, \ldots, n;\ t = 1, \ldots, T \end{aligned} \tag{1}$$

Stage 2 (scientific research):

$$\theta^2 = \min \frac{1 - \frac{1}{m + T'k}\left(\sum_{i=1}^{m}\frac{s_i^{x,t}}{\alpha^t x_{io}^t} + \sum_{t'=0}^{T'}\sum_{l=1}^{k'}\frac{s_l^{z,t-t'}}{\beta^{t'} z_{lo}^{t-t'}}\right)}{1 + \frac{1}{q}\sum_{p=1}^{q}\frac{s_p^{y,t}}{y_{po}^t}}$$

$$\begin{aligned} s.t.\quad & \sum_{j=1}^{n}\lambda_j^{2,t} \cdot \alpha^t x_{ij}^t = \alpha^t x_{io}^t - \alpha^t s_i^{x,t} \\ & \sum_{t'=0}^{T'}\sum_{j=1}^{n}\lambda_j^{2,t} \cdot \beta^{t'} z_{lj}^{t-t'} = \sum_{t'=0}^{T'} z_{lo}^{t-t'} - \sum_{t'=0}^{T'} s_l^{z,t-t'} \\ & \sum_{j=1}^{n}\lambda_j^{2,t} \cdot y_{pj}^t = y_{po}^t - s_p^{y,t} \\ & \sum_{j=1}^{n}\lambda_j^{2,t} = 1 \\ & s_i^x,\ s_l^z,\ s_p^y,\ \lambda_j^2 \geq 0 \\ & i = 1, \ldots, m;\ l = 1, \ldots, k;\ p = 1, \ldots, \mathrm{q}; \\ & j = 1, \ldots, n;\ t = 1, \ldots, T \end{aligned} \tag{2}$$

where λ^1 and λ^2 are the intensity vectors. The time

t' in formula (2) represents the period of the research projects. In the actual HEI innovation process, science and technology projects do not necessarily end within a year, many last for more than a year. Projects established in previous years that are still in the funding period continue to support the scientific research and innovation activities of the current year. Therefore, the research achievements generated in the current year may be partially or fully contributed to by the projects established in previous years. The full project period is represented by $T'+1$ in this study. The duration of projects varies across different disciplines and different funding sources. Some projects with simple research goals last for less than or for a full year, while large projects with significant research tasks may last for five years or longer. Most general projects funded by the National Natural Science Fund of and National Social Science Fund of China last approximately 3 years; as such, the value of T' is set at 2.

The term α is the shared proportion of $\boldsymbol{x}$, obtained from the statistical data. The term $\boldsymbol{\beta}$ is the effective proportion of each project at time t'. It is generally accepted that the last period has the most influence on a system (Cooper et al., 2007). As such, this study solves for different values of $\boldsymbol{\beta}$ in the project periods using the Exponential Attenuation Model. Exponential Attenuation Model determines weights, and can be flexibly applied to real decision-making problems. The decision-maker can determine the value of the decay coefficient according to information obtained at different times.

For the discrete-time data used in this study, the weight of a project's impact at period $t'(t'=1, \ldots, T')$ in its life cycle is defined as:

$$\beta_{t'} = C_o e^{\upsilon(t'-T')}$$

where C_0 is constant and $\boldsymbol{v}$ is an attenuation coefficient. The weight $\beta_{t'}\left(t'=1,\ldots,T'\right)$ is expected to meet the conditions $\sum_{t'=1}^{T'} \beta_{t'} = 1$. Therefore, $\beta_{t'}$ is solved as:

$$\beta_{t'} = \frac{e^{\upsilon t'}\left(1-e^{\upsilon}\right)}{e^{\upsilon}\left(1-e^{\upsilon t'}\right)},\ t'=1,\ldots,T' \tag{3}$$

3.2 Overall efficiency measurement

The linear programming infeasibility problem (Tone and Tsutsui, 2014) may exist under a single-period PPS. To solve this problem, some studies have introduced the global PPS (GPPS) when measuring efficiency. However, the GPPS has disadvantages in practice. Since the GPPS establishes a single reference PPS by enveloping all contemporaneous PPS, it may change when a new contemporaneous PPS is added. Therefore, the efficiency values of all *DMUs* may also change, resulting in the calculated values being unstable. Based on previous research (Oh, 2010), we construct the PPS from $t-T'$ to $t+T'$, $PPS_p = conv\{t-T',\ t-T'+1,\ \ldots\ ,\ t+T'\}$. The HEI innovation efficiency in each province is measured based on this. Consequently, the innovation efficiency under the PPS_p of each stage is defined as follows.

Stage 1 (project application):

$$\begin{aligned}
\psi^1 = \min & \frac{1-\frac{1}{m}\sum_{i=1}^{m}\frac{s_i^{x,t}}{x_{io}^t}}{1+\frac{1}{k}\sum_{l=1}^{k}\frac{s_l^{z,t}}{z_{lo}^t}} \\
s.t. \quad & \sum_{t=t-T'}^{t+T'}\sum_{j=1}^{n}\lambda_j^{1,t}x_{ij}^t = x_{io}^t - s_i^{x,t} \\
& \sum_{t=t-T'}^{t+T'}\sum_{j=1}^{n}\lambda_j^{1,t}z_{lj}^t = z_{lo}^t + s_l^{z,t} \\
& \sum_{t=t-T'}^{t+T'}\sum_{j=1}^{n}\lambda_j^{1,t} = 1 \\
& s_i^{x,t},\ s_l^{z,t},\ \lambda_j^{1,t} \ge 0 \\
& i=1,\ldots,m;\ l=1,\ldots,k; \\
& j=1,\ldots,n;\ t=1,\ldots,T
\end{aligned} \tag{4}$$

Stage 2 (scientific research):

$$\begin{aligned}
\psi^2 = \min & \frac{1-\frac{1}{m+T'k}\left(\sum_{i=1}^{m}\frac{s_i^{x,t}}{\alpha^t x_{io}^t}+\sum_{t'=0}^{T'}\sum_{l=1}^{k'}\frac{s_l^{z,t-t'}}{\beta^{t'}z_{lo}^{t-t'}}\right)}{1+\frac{1}{q}\sum_{p=1}^{q}\frac{s_p^{y,t}}{y_{po}^t}} \\
s.t. \quad & \sum_{t=t-T'}^{t+T'}\sum_{j=1}^{n}\lambda_j^{2,t}\cdot\alpha^t x_{ij}^t = \alpha^t x_{io}^t - \alpha^t s_i^{x,t} \\
& \sum_{t=t-T'}^{t+T'}\sum_{t'=0}^{T'}\sum_{j=1}^{n}\lambda_j^{2,t}\cdot\beta^{t'}z_{lj}^{t-t'} = \sum_{t'=0}^{T'}z_{lo}^{t-t'} - \sum_{t'=0}^{T'}s_l^{z,t-t'} \\
& \sum_{t=t-T'}^{t+T'}\sum_{j=1}^{n}\lambda_j^{2,t}\cdot y_{pj}^t = y_{po}^t - s_p^{y,t} \\
& \sum_{t=t-T'}^{t+T'}\sum_{j=1}^{n}\lambda_j^{2,t} = 1 \\
& s_i^x,\ s_l^z,\ s_p^y,\ \lambda_j^2 \ge 0 \\
& i=1,\ldots,m;\ l=1,\ldots,k;\ p=1,\ldots,\mathrm{q}; \\
& j=1,\ldots,n;\ t=1,\ldots,T
\end{aligned} \tag{5}$$

Furthermore, the overall efficiency of the HEIs' innovation process is calculated as:

$$\psi = \omega_1\psi_1 + \omega_2\psi_2 \tag{6}$$

where ω_1 and ω_2 are the exogenous weights of each stage. Based on previous research (Pastor et al., 2011; Xiong et al., 2018; Min et al., 2020), the values of ω_1 and ω_2 both equal 0.5 in this study [1].

4 Empirical results

4.1 The overall innovation efficiency

Fig. 5 shows the overall HEI innovation efficiency in mainland China from 2014 to 2020. The innovation efficiency showed a growth trend, continuing to increase from 0.7900 in 2014, and reaching the highest level of 0.8473 in 2020. The evolutionary process aligns with two periods of growth over the 7 years. The first period was from 2014 to 2017. At the start of this period, the HEI innovation efficiency in 2015 decreased slightly compared with 2014. In August 2015, China decided to coordinate and promote the construction of world-class universities and first-class disciplines. This was called the "Double First-Class" initiative. In October of the same year, the State Council of China issued the *Overall Plan for Promoting the Construction of World-Class Universities and Disciplines*. Urgent tasks were clarified, such as teacher team building, talent training, and scientific research level improvement. These all emphasized improvements in innovation ability. The year 2015 was also when the HEI innovation efficiency entered a stage of stable and rapid growth. The "Double First-Class" initiative of China HEI was fully launched in 2017, when the innovation efficiency also achieved the greatest increase.

In 2018, the development of HEI innovation efficiency entered the second period marked by this study. After rapid development in 2015-2017, the HEI innovation efficiency in 2018 was slightly lower compared to 2017. This may have been because the same level of effort could no longer achieve the same score after the full-scale improvements in the previous years. The data for the inputs and outputs show that the academic paper, monographs, and technology transfer income grew steadily in 2016-2018. Moreover, the increase in academic monographs and technology transfer income was higher in 2018 compared to 2017. There was a 16.87% increase in the number of monographs in 2018, reflecting an increase of more than 6 percentage points over 2017. The growth in technology transfer income was even more significant, from 14.03% in 2017 to 37.04% in 2018.

However, the research achievements produced by the funding input per unit project also increase. This confirms the assumption that maintaining the same level of HEI innovation efficiency required more effort during and after 2017. Therefore, starting from 2019, the innovation efficiency of HEI resumed the growth trend of annual increases. The annual growth rate of this stage was higher compared to the first stage. In 2019, the innovation efficiency of HEI was 0.8210, which essentially recovered to the 2017 level. By 2020, there was additional progress in improving innovation efficiency. Compared with 2019, innovation efficiency increased by 0.0263, reaching the highest level since 2014. Therefore, after the adjustment in 2018, HEI innovation efficiency resumed the growth trend of annual increases. The annual growth rate of this period was higher compared to the first period. The HEI innovation efficiency was 0.8210 in 2019, reflecting a recovery to the 2017 level. The progress in innovation efficiency further increased by 2020, as the level increased by 0.0263 over 2019, reaching the highest level since 2014.

The regional synergy of HEI innovation efficiency continuously improved alongside the level of innovation efficiency after 2014. In terms of the innovation efficiency level, none of the 31 provinces in mainland China reached a completely efficient level of the overall HEI innovation process during or before 2015. **Fig. 6** shows that the maximum value of overall innovation efficiency in 2014 was 0.9543, which increased slightly to 0.9793 in 2015. However, the value did not reach 1, which represents peak efficiency. The average value of HEI innovation efficiency in different regions also rose, with fluctuations, from 0.7900 in 2014 to 0.8473 in 2020. In terms of regional coordination, **Fig. 6** shows that in 2016 and before, the degree of coordination with respect to regional HEI innovation efficiency was relatively low and fluctuated. This was reflected in the presence of outliers. Even in 2016, the minimum value was lower than 0.5. However, there were fluctuations in the distance between the upper and lower quartiles.

[1] We have also examined the effect of different weight assignments on the overall efficiency. Details are shown in **Fig. 8** in Section 4.2.

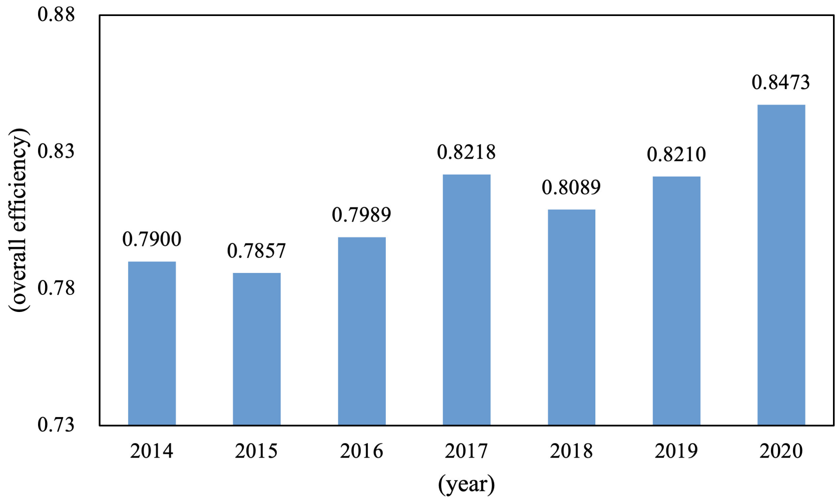


Fig 5. The HEIs' overall innovation efficiency from 2014 to 2020

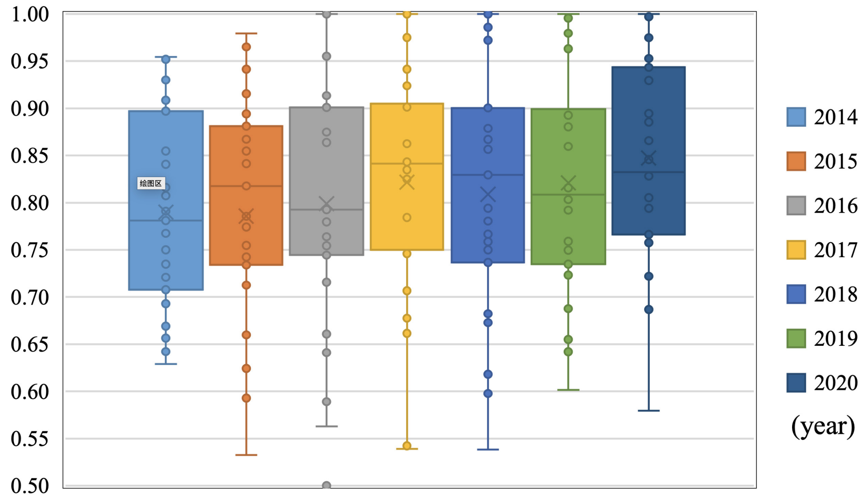


Fig 6. Box plot of the overall HEI innovation efficiency from 2014 to 2020

Table 2. Overall and stage efficiency from 2014 to 2020

		2014	2015	2016	2017	2018	2019	2020
Overall	Average	0.7583	0.7516	0.7777	0.7804	0.7726	0.7862	0.7825
	Max	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
	Min	0.4228	0.3292	0.4917	0.4928	0.5074	0.4526	0.5174
	Median	0.7941	0.7673	0.7913	0.7891	0.7576	0.7961	0.7838
	Standard deviation	0.1702	0.1614	0.1559	0.1601	0.1579	0.1611	0.1473
Stage 1	Average	0.7583	0.7516	0.7777	0.7804	0.7726	0.7862	0.7825
	Max	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
	Min	0.4228	0.3292	0.4917	0.4928	0.5074	0.4526	0.5174
	Median	0.7941	0.7673	0.7913	0.7891	0.7576	0.7961	0.7838
	Standard deviation	0.1702	0.1614	0.1559	0.1601	0.1579	0.1611	0.1473
Stage 2	Average	0.7583	0.7516	0.7777	0.7804	0.7726	0.7862	0.7825
	Max	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
	Min	0.4228	0.3292	0.4917	0.4928	0.5074	0.4526	0.5174
	Median	0.7941	0.7673	0.7913	0.7891	0.7576	0.7961	0.7838
	Standard deviation	0.1702	0.1614	0.1559	0.1601	0.1579	0.1611	0.1473

4.2 The innovation efficiency in different stages

This section analyzes HEI innovation efficiency and its dynamic evolution in the two studied stages. In the project application stage, the R&D personnel in HEI convert research ideas into project applications and apply for funding for research projects. After expert review and other processes, the projects with research value are funded; these funded projects become the output of the first stage and the input into the second stage. The second stage is the project research stage. The R&D personnel who have successfully applied for projects conduct the project research using funding support, or cooperate with other researchers to conduct research. This yields research achievements, such as academic papers, monographs, and technology transfer income. **Fig. 7** reflects the efficiency of each stage and the overall efficiency of the HEI innovation process in mainland China from 2014 to 2020.

The efficiency of the second stage was consistently higher compared to the first stage throughout the study period. The level of utilization of innovative resources, such as R&D personnel and R&D funds in the project research stage, was higher compared to the project application stage. This outcome can be analyzed through the lens of the actual research process. In the project application stage, researchers consider their research ideas as valuable, leading them to apply for funding support. However, some of the applications may not be feasible, due to lack of research design, professional foundation, or practical conditions. Therefore, most projects with low feasibility or low funding value are eliminated in the first stage. Consequently, the projects researched in the second stage are projects that are considered to have research value. As such, the efficiency should be higher compared to the first stage. We have also examined the effect of different weight assignments on the overall efficiency. It can be seen from **Fig. 8** that, at the national level, the larger the weight of the second stage, the higher the overall efficiency value obtained at the end. This feature also confirms that the efficiency value of the second stage is higher than that of the first stage.

Similar to the changing trend of the overall HEI innovation efficiency, the innovation efficiency of both Stages 1 and 2 increased in 2014-2020. The efficiency of the project application stage rose in fluctuation, from 0.7583 in 2014 to 0.7825 in 2020. Among them, the highest level appeared in 2019, which was 0.7862. In contrast, there was a more significant increase in innovation efficiency in the project research stage, from 0.8216 in 2014 to 0.9121 in 2020, which is 3.74 times the increase in efficiency in the project application stage. The change in the efficiency gap between the two sub-stages can be divided into two periods. In the first period, from 2014 to 2017, the efficiency gap between the two sub-stages first narrowed and then increased. Starting in 2018, the efficiency gap between the two sub-stages steadily expanded, reaching the highest value in 7 years by 2020.

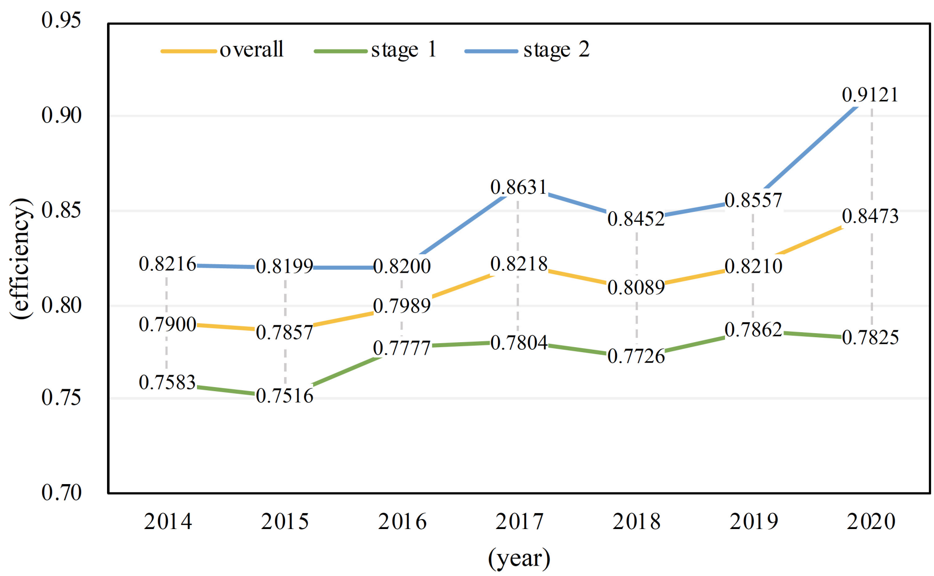
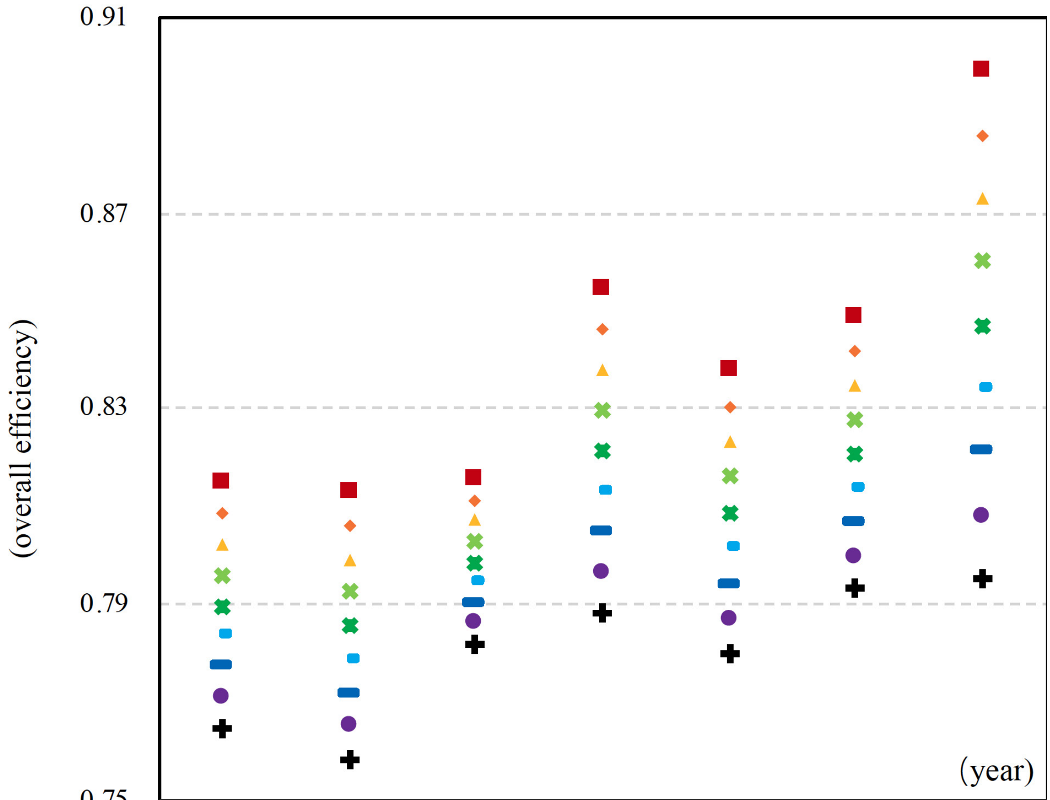


Fig 7. Efficiency in Stages 1 and 2, and the overall HEI innovation efficiency from 2014 to 2020



	2014	2015	2016	2017	2018	2019	2020
ω1=0.1, ω2=0.9	0.8153	0.8131	0.8158	0.8549	0.8380	0.8488	0.8991
ω1=0.2, ω2=0.8	0.8090	0.8062	0.8115	0.8466	0.8307	0.8418	0.8862
ω1=0.3, ω2=0.7	0.8026	0.7994	0.8073	0.8383	0.8234	0.8349	0.8732
ω1=0.4, ω2=0.6	0.7963	0.7926	0.8031	0.8300	0.8162	0.8279	0.8603
ω1=0.5, ω2=0.5	0.7900	0.7857	0.7989	0.8218	0.8089	0.8210	0.8473
ω1=0.6, ω2=0.4	0.7836	0.7789	0.7946	0.8135	0.8017	0.8140	0.8343
ω1=0.7, ω2=0.3	0.7773	0.7721	0.7904	0.8052	0.7944	0.8071	0.8214
ω1=0.8, ω2=0.2	0.7709	0.7652	0.7862	0.7970	0.7871	0.8001	0.8084
ω1=0.9, ω2=0.1	0.7646	0.7584	0.7820	0.7887	0.7799	0.7932	0.7955

Fig. 8. Different overall efficiency values under different weight assignments.

4.3 Characteristics of the provincial HEI innovation efficiency

Taking the efficiency of Stage 1 as the abscissa and the efficiency of Stage 2 as the ordinate, the provinces are plotted in a coordinate graph. Using an efficiency value of 0.5 as the starting point, and an efficiency value of 0.75 as the center line, the coordinate graph is divided into four quadrants, shown in **Fig. 8**. Provinces in the first quadrant have high efficiency levels in both the project application and project research stages. This indicates that the HEI innovation efficiency level of such provinces is in the leading position both overall and at both stages of the innovation process. Correspondingly, the provinces in the fourth quadrant lag behind in both the project application and project research stages and need to improve their HEI innovation efficiency. The provinces in the second and fourth quadrants have an advantage in one area, but the level needs to be improved in another. Provinces in the second quadrant have a higher level of project input resources, and those in the fourth quadrant have higher project application efficiency. However, both types of provinces need to invest effort to achieve efficient HEI innovation processes.

Fig. 9 shows all 31 provinces are distributed in the four quadrants, with most provinces being in the first and second quadrants. The fewest provinces are in the third quadrant, denoting the provinces with low project application and project research efficiency. This indicates that the HEI innovation efficiency is good or is in a good development stage. There are also not many provinces in the fourth quadrant. More provinces are located in the second quadrant, with a relatively high level of innovation resource utilization. To improve innovation efficiency, more efforts are needed in the project application stage, such as improving the quality of project application. **Fig. 8** also reflects the overall HEI innovation efficiency, represented by the size of the points. A larger point size is associated with a higher overall level of efficiency. The final overall innovation efficiency can only be good if the project performs well in both the project application and project research stages. This also represents the common direction that all provinces in the second, third, and fourth quadrants should work on.

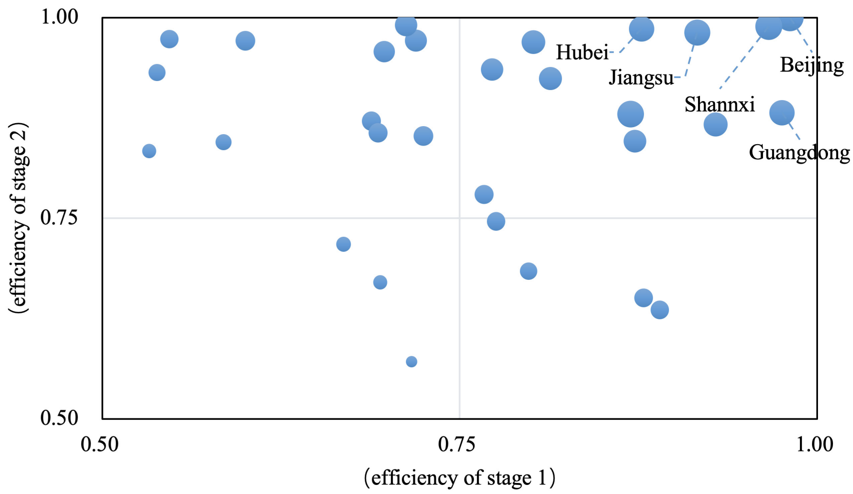


Fig 9. Efficiency in stage 1, 2, and the overall HEI innovation efficiency of the 31 provinces in mainland China from 2014 to 2020

Note: The size of the dots in the figure represents the level of the provincial HEI innovation efficiency. The larger the size, the higher the efficiency value.

From the perspective of the comprehensive innovation efficiency of HEI, during the study's observation period, the top five provinces in the country were Beijing, Shannxi, Jiangsu, Hubei, and Guangdong (**Fig. 8**). The five provinces were not geographically related, but shared similar characteristics with respect to university rankings. According to Nature Index 2021, these five provinces had the largest number of colleges and universities, except Shanghai. The top 100 mainland universities in Beijing, Jiangsu, and Guangdong each have more than 10 provinces with 13, 17, and 10 top universities, respectively. Hubei and Shaanxi each had 6 and 5 top universities, respectively.

These five provinces can be divided into three types. The first type performs well in the project application and project research stage and includes Beijing and Shaanxi. The second type performs better in the project application stage than the project research stage and is represented by Guangdong. The third type has high levels of project research efficiency, but relatively low project application efficiency; this type is represented by Jiangsu and Hubei. If the efficiency of the project application stage can be further improved, the innovation efficiency can also be improved. This happened in Shanghai, which is a province that serves as an important driving force for China's innovation and development. The evaluation results show that for 2014-2020, the overall HEI innovation efficiency in Shanghai did not lead the other country's regions in a similar way as its regional innovation capability. In 2020, 8 universities in Shanghai ranked among the top 100 in mainland China according to the Nature Index 2021. However, there was a low level of efficiency in the project application stage, at only 0.7726. As such, despite the high project research efficiency, its final HEI innovation efficiency is only 0.8540, ranking 14th among the 31 provinces.

5 Conclusion and discussion

This study evaluated the efficiency of HEI innovation using an improved two-stage DEA model. The overall innovation efficiency, and the efficiency of the two sub-stages of project application and project research, were measured for 31 provinces in mainland China from 2014 to 2020. This study generated the following three main conclusions.

First, the overall HEI innovation efficiency experienced a two-period growth process from 2014 to 2020. The first period was 2014-2017, during which HEI innovation efficiency experienced a slight decline and then increased. The second period was from 2018 to 2020, during which the innovation efficiency also first decreased and then increased. However, the fluctuation in innovation efficiency was more significant in this period compared to the first period, regardless of whether there was an increase or decrease. Overall, HEI innovation efficiency in mainland China increased from 0.7900 in 2014 to the highest level of 0.8473 in 2020. The change in the overall HEI innovation efficiency was more consistent with the gestation and launched process of the “Double First-Class” initiative of China. Because HEIs want to be included in the list of “Double First-Class” initiative, it was more significant to assess the improvement of HEI innovation efficiency in the year when the initiative was launched. After the official implementation of the “Double First-Class” initiative, HEI underwent a one-year adjustment, and during its implementation period, it significantly promoted the improvement of HEI innovation efficiency. This resulted in the larger growth rate of HEI innovation efficiency in the second period.

Second, the efficiency was generally higher during the project research stage than the project application stage. During 2014-2020, the annual average project application efficiency of HEI was 0.7728, which was significantly lower than the annual average project research efficiency of 0.8482. This highlights two key points. First, the level of utilization of innovative resources such as R&D personnel and R&D funds was higher in the project research stage compared to the project application stage. Second, when considering the effectiveness of the project funding review process, in the first stage, applications with low feasibility or innovation value are screened out, improving the overall efficiency level of the second stage. Both the project application stage and the project research stage have similar changing trends with respect to the overall HEI innovation efficiency, which also experienced two periods of decline and then growth. The efficiency gap between the two sub-stages gradually increased over time. In 2020, the efficiency of the project research stage exceeded 0.9, while the efficiency of the project application stage remained at 0.7.

Third, the research efficiency of most provinces exceeded 0.8, while there remained room for improvement in the efficiency of the project application stage. The 31 provinces were divided into three types according to their performance at different stages. The first type included provinces with similar levels of performance during project application and project research; these provinces made up 32.26% of the total. The second type included provinces where the performance level was highest during the project application stage compared to the project research stage. There were only 6 such provinces, making up a small proportion of the total. The third type included provinces with a higher efficiency level during the project research stage compared to the project application stage. There were 15 such provinces, accounting for about half of the total. The top five provinces with respect to HEI innovation efficiency were: Beijing, Shannxi, Jiangsu, Hubei, and Guangdong. The universities in these five provinces have strong academic influence and competitiveness. The number of the top 100 mainland China universities listed in the Nature Index 2021 in these five provinces also ranked highest in mainland China.

Despite the progress of HEI’s innovation efficiency, there is still room for improvement. First, importance should be attached to the improvement of the evaluation system. A proper innovation evaluation system can help HEIs judge the strengths and weaknesses of their innovation capabilities and better tap the potential of HEI innovation. To further improve HEI’s innovation efficiency, we should focus on the quantity of HEI innovation achievements and the quality of innovation achievements. Therefore, it is necessary to adhere to the evaluation orientation centered on innovation quality, performance, and contribution, and comprehensively and accurately reflect the quality of achievements, transformation and application performance, and actual contribution to economic and social development.

Second, optimizing the innovation resource allocation mechanism of HEIs can be a promotion for the improvement of HEI innovation efficiency. Innovation resources are the material basis and the collection of various resource elements in innovation activities. However, innovation resources are scarce, and improving the efficiency of scientific and technological resources is essential for enhancing innovation efficiency. To optimize the innovation resource allocation mechanism of HEI, we should adhere to demand orientation and problem orientation and proceed from the country's urgent and long-term needs to solve practical problems truly. At the same time, it is necessary to focus on innovation priorities, clarify the critical directions of innovation resource allocation, focus on original innovation capabilities, and promote key common technological innovations.

Third, consideration should be given to promoting the cultivation of innovative talents. The innovative talent team is a key task to achieving high-level scientific and technological self-reliance and self-improvement, which is of great significance for enhancing HEI's original innovation capability and improving innovation resource utilization efficiency. To further improve innovation efficiency, HEI can build a multi-level talent pattern consisting of strategic, leading, young, and other innovative talents. Furthermore, HEI should innovate the way of recruiting talents, empower innovative talents with scientific research autonomy, and continuously release and stimulate researchers' entrepreneurial enthusiasm and motivation. In addition, it is necessary to reduce the transactional tasks and ensure that researchers can focus the research activities and practical transformation of innovation achievements.

This study involved innovative research on HEI innovation efficiency, however, some areas would benefit from additional research. Future studies should consider the following two aspects. First, deeper analyses with the HEIs as DMUs are needed to identify how the different types of HEIs affect regional HEI innovation efficiency. Second, policy effectiveness tests should be conducted to identify specific improvements in HEI innovation efficiency from actions such as the "Double First-Class" from an empirical analysis perspective.

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