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ECONOMIC AND ENVIRONMENTAL EFFICIENCY OF JOINT R&D BETWEEN UNIVERSITIES AND FIRMS

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Abstract. China's total R&D funding has increased from CNY 89.6 billion in 2000 to CNY 2,442.6 billion in 2020 or by 27 times in 20 years. Although a large amount of literature has analyzed China's R&D efficiency, scant studies have targeted second-stage economic and environmental efficiencies and rarely considered both university and industrial R&D. This research thus uses the Parallel Two-stage Undesirable Dynamic Model to evaluate the R&D efficiencies of universities and industry and examines their impact on the economy and the environment. The empirical results are as follows. 1) There are differences in the R&D and environmental efficiency of various regions in China with the eastern part being the highest, the western part second, and the central part the lowest. 2) The input index efficiency of universities is generally higher than that of industry. 3) The linkage effect between universities and the local economy and the environment is higher than that of industry.

Keywords: R&D efficiency, environment, Parallel Two-stage.

JEL Classification: O11, O32, O44.

Introduction

Investment used in research and development (R&D) is crucial to the advancement of new technologies and is one of the main factors of national progress. The total amount spent by all resident companies, research institutes, universities and government laboratories in a country is called domestic R&D expenditure, as defined by the Organisation for Economic Co-operation and Development [OECD]. Figure 1 shows the six countries and regions with the largest cumulative R&D input in the OECD since 2000, and uses 2010 as the base year and Purchasing Power Parities (PPPs) to measure gross domestic spending on R&D of each country with USD constant prices and percentage of GDP. Since 2000, the United States has

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been ahead of other countries in R&D expenditure with the other countries always maintaining a certain level. However, China has exhibited a clear upward trend since 2004 and surpassed Japan in 2009. At the same time, China's large population base is a factor that cannot be ignored, it gives us an advantage in increasing our total R&D investment. The proportion of R&D investment in GDP, growth rate and other indicators also need to be concerned. Looking back on China's past R&D policies, the proportion of R&D expenditure in GDP increased from 2.2% during the 12th Five Year Plan to 2.5% in the 13th Five Year Plan. China has already begun to work hard to meet this goal, and R&D spending in 2020 did grow 10% to a record US$378 billion (National Bureau of Satistics, 2021).

China's rapid economic growth has enabled it to invest more resources into R&D and create further development. Funding for basic research during the 13th Five-Year Plan period basically doubled, reaching 133.6 billion CNY in 2019, which is the first time that the percentage of funds used in R&D in the whole society exceeded 6%. The target of further increase in investment in basic research is expected to be achieved during the 14th Five-Year Plan. The central government is continuing to increase investment to guide enterprises and society to also advance investment into basic research (Ministry of Science and Technology of the People's Republic of China, 2021).

According to the announcement of the Chinese official authorities, from 2006 to 2019 the R&D funding of Chinese enterprises, research institutions, and colleges and universities has maintained a steady growth trend. In 2019, the internal R&D expenditures of Chinese enterprises, research institutions, and colleges and universities were 169.218 billion CNY, 300.88 billion CNY, and 179.66 billion CNY, or an increase of 11.1%, 14.5%, and 23.2% from 2018, respectively. The proportions of R&D expenditures were respectively 76.4%, 13.9%, and 8.1%. In 2019, among government R&D funds, those flowing to research institutions accounted for 56.9%, those to colleges and universities accounted for 23.11%, those to enterprises accounted for 14.3%, and those flowing to other departments accounted for 5.7%. The development of high-tech industries is of great significance, the national economy benefits

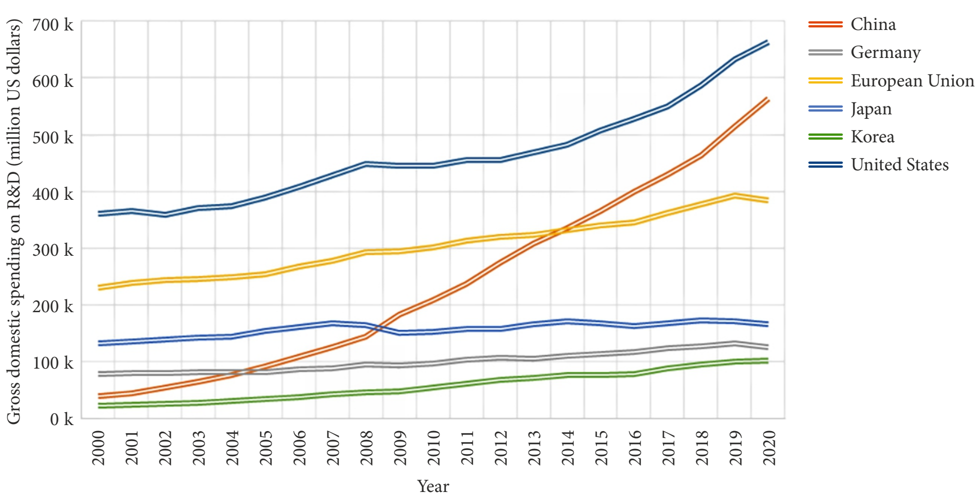

Figure 1. Trend of total R&D expenditure by countries (total, million US dollars) (source: OECD, 2021)

from it, and the industrial structure will be upgraded as a result. Universities are also key source of knowledge for corporate innovation and a source of economic growth. Therefore, how to use limited funds and provide a good external institutional environment to improve R&D performance is an important issue.

Many studies in the literature have discussed R&D efficiency (Hervás-Oliver et al., 2021; Kim & Shin, 2019; Li et al., 2019; Salas-Velasco, 2018; Zeng, 2017; Wang et al., 2016; Yanhui et al., 2015; Costa-Campi et al., 2014). Sun et al. (2019) and Chen et al. (2021) present how green innovation affects R&D efficiency. Most past studies only discussed companies or schools. For example, some scholars focused on the R&D efficiency of companies or technology industries, but did not take universities into consideration (Zhong et al., 2011; Liu et al., 2020). Others noted the R&D efficiency of universities (Beasley, 1995; Kreiling et al., 2020; Temel et al., 2021), but ignored the R&D contribution of enterprises and high-tech industries.

Cohen et al. (2002) confirmed that R&D by universities and governments is very important to industry and has an important impact on most manufacturing sectors. Belderbos et al. (2004) found that R&D cooperation between enterprises and universities can help enterprises innovate and improve their performance. Abramovsky et al. (2007) believed that the direction of corporate drug R&D is related to related university research (such as the Department of Chemistry). The evidence illustrates a collaborative and complementary relationship between enterprise R&D and university R&D. Thus, when exploring the R&D efficiency of a country, it is necessary to analyze the R&D efficiency of national enterprises and universities at the same time. With the continuous deepening of the combination of "Industry-Teaching-Research", the R&D cooperation between universities and enterprises will become an inevitable trend. Enterprises need universities to provide talents and technology, and universities also need to seek support from society and enterprises. The joint R&D of the two will help to organically combine the scientific research ability of universities with the market-oriented operation of enterprises, promote the talent training of universities, accelerate the scientific and scientific and technological progress of enterprises, realize the "Win-Win" between colleges and enterprises, and will benefit the social and environmental friendly economic progress (D'Aspremong & Jacquemin, 1988; Nie et al., 2022a, 2022b; Wang & Nie, 2021).

Some scholars investigated the R&D of universities and enterprises (Maietta, 2015; Li & Tan, 2020), but most methods used are regression analysis and static analysis, mainly analyzing the factors that affect R&D. Some scholars introduced the concept of network into the topic. For example, Wang et al. (2020) used a two-stage approach to research the R&D and business efficiency of enterprises. Feng et al. (2021) studyed the efficiency of R&D and marketing between countries. Although different R&D activities can be further distinguished in the model, there is still room for improvement in research methods. Therefore, our study uses the dynamic network DEA model proposed by Tone and Tsutsui (2014) and the parallel DEA model proposed by Kao (2009), which uses the concepts of universities and industry as two subsystems. This research considers economic and environmental issues and presents the impact of R&D activities on the economy and the environment in the second stage. While the important role played by R&D in development is re-emphasized, environmental issues are also fully considered. There are three contributions from this research. First, previous literature only considered research and development in universities or industries alone. Our study introduces the concept of a parallel system and analyzes the R&D efficiency performance of universities and industries. Second, most studies in the past used static analysis to discuss factors affecting R&D. We incorporate the concept of a carry-over variable into the model to analyze intertemporal changes. Third, this research discusses the efficiency of research and development and also incorporates economic and ecological factors into the model. The economic effects of R&D are further explored in this study, environmental pollution problems such as CO_2 and SO_2 caused by R&D activities are also considered.

1. Methods

The main theoretical basis of DEA is the CCR model in 1978, the BCC model in 1984, and the Slacks Based Measure (SBM) model proposed by Tone in 2001. Many different follow-up models have expanded from these models. Among them, Färe and Grosskopf (1996) regarded the production process as a network that has three parts: input, output, and intermediate good. Färe et al. (2007) proposed the Network Data Envelopment Analysis (NDEA) model, stated that many secondary production technologies constitute the production process and can be considered as Sub-DMUs. The network DEA model overcomes the shortcomings of the traditional DEA which regards the secondary production technology as a "black box". At the same time, the secondary input research methods are applied, so that the impact of input and intermediate products on the production process can be studied (Cook & Hababou, 2001; Seiford & Zhu, 1999). Tone and Tsutsui (2009) further proposed a weighted SBM network data envelopment analysis model. Each department can be considered as a Sub-DMU for independent research, and the relationship between decision making units lays the foundation for network DEA analysis. This is the progress of network DEA compared with traditional DEA. Since there is more than one period of production activity in the sector, dynamic DEA models need to be introduced (Amirteimoori, 2013; Wu et al., 2016b). When different departments and periods are explored at the same time, network DEA and dynamic DEA need to be organically combined, that is, Dynamic Network DEA appears (Tone & Tsutsui, 2014). A parallel system is a basic type of network structure, where the DMU in the production process is composed of multiple subsystems. Kao (2009) discussed the relationship between partial and overall efficiency, and proposed a parallel DEA model to study it. Castelli et al. (2004) and Färe and Grosskopf (2000) used single-level and two-level hierarchical structures to calculate the efficiency of each combination, where each DMU is composed of multiple consecutive parallel subsystems. Kao and Hwang (2010) developed the relationship model of series and parallel network structures to provide the efficiency of the system and composition. According to the study, multiple DMUs can be considered as a parallel structure. When each DMU has the same number of processes, different processes can still perform the same function, and such parallel systems are classified as multi-part and multi-functional types (Kao, 2012, 2017; Wu et al., 2016a; Yu & Shi, 2014; Zha & Liang, 2010). The Dynamic Network DEA model ignores the undesirable factors, but sub-units have different functions when input and output are different. To overcome this problem, our study combines the Dynamic Network DEA model and the Parallel DEA model and undesirable factors and proposes the Parallel Two-stage Undesirable Dynamic Model for evaluating

China's R&D and economic and environmental efficiency from 2015 to 2019. The model is able to calculate the efficiency of the whole system and individual departments. The relevant departments can effectively reallocate resources to different departments in the system based on efficiency, thus improving system efficiency.

Parallel Two-stage Undesirable Dynamic Model

Suppose that there are n DMUs denoted by $DMU_j\left(j=1,\ldots,n\right)$, with each having k divisions $\left(k=1,\ldots,K\right)$ and T time periods $\left(t=1,\ldots,T\right)$. Each DMU has an input and output at time period t and a carry-over (link) variable to the next $t+1$ time period.

Inputs and outputs

$X_{ijk}^{t}\in R_{+}\left(i=1,\ldots,m_k;j=1,\ldots,n;k=1,\ldots,K;t=1,\ldots,T\right)$ refers to input i at time period t for DMU_j division k; In stage 1.1, the industrial innovation stage, the R&D personnel of industrial enterprises and R&D internal expenditure of industrial enterprises are input items. In stage 1.2, or the university innovation stage, R&D personnel of universities and R&D internal expenditure of universities are inputs. In stage 2, or the economic and environmental stage, energy consumption is an input item.

$Y_{rjk}^{t}\in R_{+}\left(r=1,\ldots,r_k;j=1,\ldots,n;k=1,\ldots,K;t=1,\ldots,T\right)$ refers to output r in time period t for DMU_j division k; Y_{rjk}^{t}: number of new product projects of industrial enterprises, number of patents, industrial sales revenue, and market turnover are output items of stage 1.1, school R&D projects and academic and international exchange papers are output items of stage 1.2, and GDP is stage 2 desirable output item. Industrial waste, industrial CO_2, and industrial SO_2 emissions are undesirable output items of stage 2.

Links

$Z_{j(kh)_l}^{t}\in R_{+}(j=1,\ldots,n;l=1,\ldots,L_{hk};t=1,\ldots,T)$ are the period t links from DMU_j division k to division h, with L_{hk} being the number of k to h links; $Z_{j(kh)_l}^{t}$: number of patents, industrial sales revenue, market turnover, and academic and international exchange papers are selected as the link indicators in the industrial innovation stage and university innovation stage.

Objective function

Overall efficiency:

$$\theta_0^{*}=\min\frac{\sum_{t=1}^{T}W^t\left[\sum_{k=1}^{K}W^k\left[1-\frac{1}{m_k+linkin_k+ninput_k}\left(\sum_{i=1}^{m_k}\frac{s_{ijk}^{t-}}{x_{ijk}^{t-}}+\sum_{(kl)_l=1}^{linkin_l}\frac{s_{j(kh)_l ing}^{t}}{z_{j(kh)_l ing}^{t}}+\sum_{k_l}^{ninput}\frac{s_{jk_l input}^{(t,t+1)}}{z_{jk_l input}^{(t,t+1)}}\right)\right]\right]}{\sum_{t=1}^{T}W^t\left[\sum_{k=1}^{K}W^k\left[1-\frac{1}{r_{1k}+r_{2k}}\left(\sum_{r=1}^{r_{1k}}\frac{s_{rjkgood}^{t+}}{y_{rjkgood}^{t}}+\sum_{r=1}^{r_{2k}}\frac{s_{rjkbad}^{t-}}{y_{rjkbad}^{t}}\right)\right]\right]}. \quad (1)$$

Subject to:

Industrial innovation stage 1.1

$$x_{ij1.1}^{t} = \sum_{j=1}^{n} X_{1.1}^{t} \lambda_{1.1}^{t} + s_{ij1.1}^{t-} \left(\forall t\right);$$

$$y_{rj1.1good}^{t} = \sum_{j=1}^{n} Y_{1.1good}^{t} \lambda_{1.1}^{t} - s_{rj1.1good}^{t+}, \left(\forall t\right);$$

$$\lambda_{1.1}^{t} \geq 0,\ s_{ij1.1}^{t-} \geq 0,\ s_{rj1.1good}^{t+} \geq 0,\ \left(\forall t\right);$$

$$Z_{j(1.1,2)_{l} in}^{t} = Z_{(1.1,2)_{l} in}^{t} \lambda_{k}^{t} + S_{j(1.1,2) in}^{t} \left(\left(1.1,2\right) in\right).$$

University innovation stage 1.2

$$x_{ij1.2}^{t} = \sum_{j=1}^{n} X_{1.2}^{t} \lambda_{1.2}^{t} + s_{ij1.2}^{t-} \left(\forall t\right);$$

$$y_{rj1.2good}^{t} = \sum_{j=1}^{n} Y_{1.2good}^{t} \lambda_{1.2}^{t} - s_{rj1.2good}^{t+}, \left(\forall t\right);$$

$$\lambda_{1.2}^{t} \geq 0,\ s_{ij1.2}^{t-} \geq 0,\ s_{rj1.2good}^{t+} \geq 0,\ ,\left(\forall t\right);$$

$$Z_{j(1.2,2)_{l} in}^{t} = Z_{(1.2,2) in}^{t} \lambda_{k}^{t} + S_{j(1.2,2) in}^{t} \left(\left(1.2,2\right) in\right).$$

Economic and environmental stage 2

$$x_{ij2}^{t} = \sum_{j=1}^{n} X_{2}^{t} \lambda_{2}^{t} + s_{ij2}^{t-} \left(\forall t\right);$$

$$y_{rj2good}^{t} = \sum_{j=1}^{n} Y_{2good}^{t} \lambda_{2}^{t} - s_{rj2good}^{t+} \left(\forall t\right);$$

$$y_{rj2bad}^{t} = \sum_{j=1}^{n} Y_{2bad}^{t} \lambda_{2}^{t} + s_{rj2bad}^{t-} \left(\forall t\right);$$

$$\lambda_{2}^{t} \geq 0,\ s_{ij2}^{t-} \geq 0,\ s_{rj2good}^{t+} \geq 0\left(\forall t\right);$$

$$e\lambda_{k}^{t} = 1 \ \left(\forall k, \forall t\right);$$

$$\sum_{j=1}^{n} Z_{jk_{1}\alpha}^{(t,(t+1))} \lambda_{jk}^{t} = \sum_{j=1}^{n} Z_{jk_{1}\alpha}^{(t,(t+1))} \lambda_{jk}^{t+1} \left(\forall k, \forall t\right);$$

$$\sum_{j=1}^{n} Z_{jk_{1}\alpha}^{(t,(t+1))} \lambda_{jk}^{t} = \sum_{j=1}^{n} Z_{jk_{1}\alpha}^{(t,(t+1))} \lambda_{jk}^{t+1} + S_{ok_{l}input}^{(t,t+1)} \ \ (k_{l} = 1, \ldots, ninput_{k};\ \forall k, \forall t);$$

$$S_{ok_{l}input}^{(t,t+1)} \geq 0,\ (\forall k, \forall t). \tag{2}$$

(b) Period and division efficiencies

(b1) Period efficiency:

$$\partial_0^* = \min \frac{\sum_{k=1}^{K} W^k \left[1 - \frac{1}{m_k + linkin_k + ninput_k} \left(\sum_{i=1}^{m_k} \frac{s_{ijk}^{t-}}{x_{ijk}^{t-}} + \sum_{(kl)_l=1}^{linkin_l} \frac{s_{j(kh)_l ing}^{t}}{z_{j(kh)_l ing}^{t}} + \sum_{k_l}^{ninput} \frac{s_{jk_l input}^{(t,t+1)}}{z_{jk_l input}^{(t,t+1)}} \right) \right]}{\sum_{k=1}^{K} W^k \left[1 - \frac{1}{r_{1k} + r_{2k}} \left(\sum_{r=1}^{r_{1k}} \frac{s_{rjkgood}^{t+}}{y_{rjkgood}^{t}} + \sum_{r=1}^{r_{2k}} \frac{s_{rjkbad}^{t-}}{y_{rjkbad}^{t}} \right) \right]}. \quad (3)$$

(b2) Division efficiency:

$$\phi_0^* = \min \frac{\sum_{t=1}^{T} W^t \left[1 - \frac{1}{m_k + linkin_k + ninput_k} \left(\sum_{i=1}^{m_k} \frac{s_{ijk}^{t-}}{x_{ijk}^{t-}} + \sum_{(kl)_l=1}^{linkin_l} \frac{s_{j(kh)_l ing}^{t}}{z_{j(kh)_l ing}^{t}} + \sum_{k_l}^{ninput} \frac{s_{jk_l input}^{(t,t+1)}}{z_{jk_l input}^{(t,t+1)}} \right) \right]}{\sum_{t=1}^{T} W^t \left[1 - \frac{1}{r_{1k} + r_{2k}} \left(\sum_{r=1}^{r_{1k}} \frac{s_{rjkgood}^{t+}}{y_{rjkgood}^{t}} + \sum_{r=1}^{r_{2k}} \frac{s_{rjkbad}^{t-}}{y_{rjkbad}^{t}} \right) \right]}. \quad (4)$$

(b3) Division period efficiency:

$$\rho_0^* = \min \frac{1 - \frac{1}{m_k + linkin_k + ninput_k} \left(\sum_{i=1}^{m_k} \frac{s_{ijk}^{t-}}{x_{ijk}^{t-}} + \sum_{(kl)_l=1}^{linkin_l} \frac{s_{j(kh)_l ing}^{t}}{z_{j(kh)_l ing}^{t}} + \sum_{k_l}^{ninput} \frac{s_{jk_l input}^{(t,t+1)}}{z_{jk_l input}^{(t,t+1)}} \right)}{1 - \frac{1}{r_{1k} + r_{2k}} \left(\sum_{r=1}^{r_{1k}} \frac{s_{rjkgood}^{t+}}{y_{rjkgood}^{t}} + \sum_{r=1}^{r_{2k}} \frac{s_{rjkbad}^{t-}}{y_{rjkbad}^{t}} \right)}. \quad (5)$$

Through the above, the overall efficiency, period efficiency, division efficiency and division period efficiency can be calculated separately (Chen et al., 2010).

2. Empirical study

2.1. Data and variables

On the basis of the Parallel Two-stage Undesirable Dynamic Model, this study evaluated the R&D and innovation stages, economic and environmental stages of universities and enterprises in 28 provinces in China from 2015 to 2019.

2.1.1. Explanation of variables

At the stage of industrial R&D innovation, the input indicators are industrial enterprises' R&D personnel and internal expenditure on R&D. The number of new product projects, patents, sales revenue and market turnover of industrial enterprises are output indicators. In the R&D innovation stage of universities, the corresponding R&D personnel and R&D internal expenditure are the input indicators. School R&D projects and academic and international exchange papers are output items. In the economic and environmental stage, energy consumption is an input item, and GDP is a good output item. Industrial waste, industrial CO_2 emissions, and industrial SO_2 emissions are the undesirable output items of the second stage. At the same time, the number of patents, industrial sales revenue, market turnover and academic and international exchange paper indicators are used as links with universities and industrial R&D innovation stage and the next stage. Table 1 shows the details of each indicator.

Industrial sales revenue, market turnover, R&D personnel of industrial enterprises, R&D internal expenditure of industrial enterprises, number of new product projects, patents, and number of new product projects of industrial enterprises come from the 2015–2019 China Statistical Yearbook, while R&D personnel of universities, R&D internal expenditure of universities, school R&D projects, academic and international exchange papers come from the data published on the official website of the Ministry of Education of China.

The specific explanation of the input-output indicators goes as follows:

① R&D personnel of universities: It refers to the university teaching and research personnel who have engaged in research and development work for more than 10% of their total teaching and research time in the statistical year. ② R&D Internal Expenditure of Universities: It refers to the expenditure of universities on scientific research and experimental development activities, namely, basic research, applied research and experimental development. ③ School R&D projects: It is the sum of the number of basic research, application foundation and experimental development projects. Refers to the number of international R&D projects in ordinary colleges and universities that established and carried out research in the current year, and continued to conduct research in previous years, but does not in-

Table 1. Input and Output Variables

Stage	Variables		Unit
Industrial Innovation Stage	Input	R&D personnel of Industrial Enterprises	Person
		R&D Internal Expenditure of Industrial Enterprises	10,000 CNY
	Output	Number of New Product Projects of Industrial Enterprises	Project
	Link	Industrial sales revenue and market turnover	100 million CNY
		Number of patents	Number
University Innovation Stage	Input	R&D personnel of Universities	People
		R&D Internal Expenditure of Universities	1,000 CNY
	Output	School R &D projects	Project
	Link	Academic and international exchange papers	Article
		School technology transfer income	1,000 CNY
Economic and Environment stage	Input	Energy consumption	Ten thousand tons
	Output	GDP	100 million CNY
		Industrial waste	Ten thousand tons
		Industrial CO_2	Ten thousand tons
		Industrial SO_2	Tons

clude commissions number of R&D projects carried out by foreign units. ④ Academic and international exchange papers: Number of papers published for universities and exchanged at international academic conferences. The following three conditions should be met: (1) the research results published for the first time; (2) the author's conclusions and experiments can be repeated and verified by peers; (3) the scientific and technological community can be cited after publication. ⑤ R&D personnel of industrial enterprises: It refers to the personnel involved in the research, management and auxiliary work of research and experimental development projects in industrial industries above designated size. ⑥ R&D internal expenditure of industrial enterprises: refers to the R&D expenditures of corporate industrial enterprises whose main business income is more than CNY 20 million per year. ⑦ Number of new product projects of industrial enterprises: a new product refers to a brand-new product developed and produced using new technical principles, new design concepts, or a significant improvement over the original product in a certain aspect such as structure, material, and craftsmanship. ⑧ School R &D projects: In the school, the net income of technology holders transferring or supplying technology to others. ⑨ Number of patents: the number of invention patents authorized by relevant intellectual property departments. ⑩ Number of new product projects of Industrial enterprises: scientific research tasks entrusted by industrial institutions to ordinary colleges and universities. ⑪ Industrial sales revenue and market turnover: refers to the amount of technical transactions in the sales revenue of new industrial products and the total transaction volume of registered contracts. The model structure of this research is shown in Figure 2.

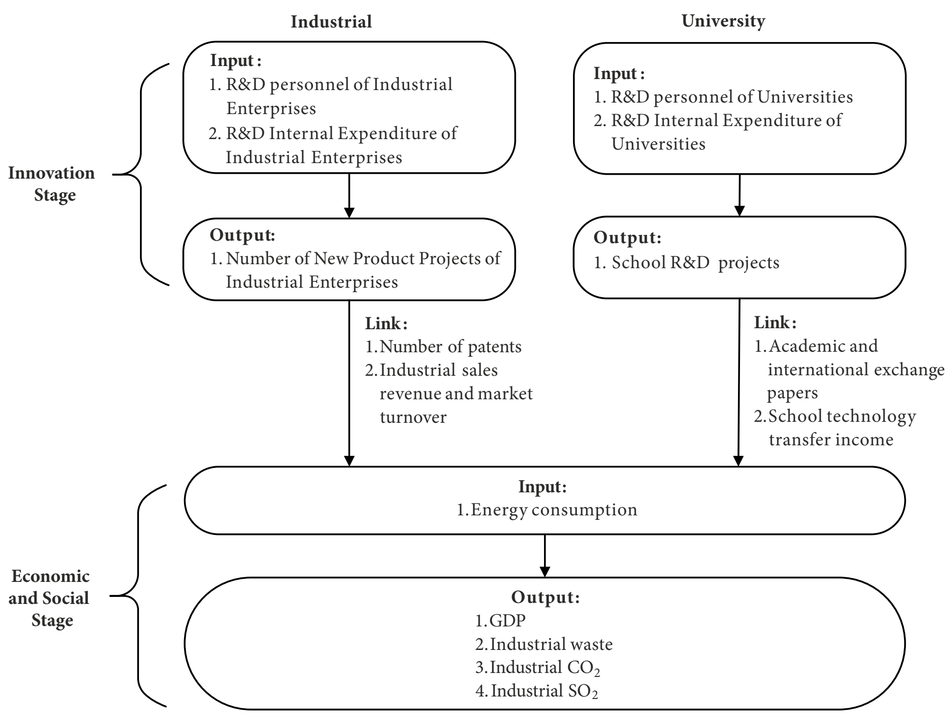

Figure 2. Model structure

2.1.2. Geographical division

The study is based on 28 provinces (including autonomous regions and municipalities directly under the central government) in China. According to the Seventh Five-Year Plan, China is divided into three economic regions: East, Central and West. Among them, Inner Mongolia and Guangxi are classified as such because their GDP per capita is comparable to the average level of western provinces. For details, see Table 2.

Table 2. Areas in China

Region	Provinces and Municipalities
Eastern	Beijing, Tianjin, Shanghai, Liaoning, Hebei, Shandong, Jiangsu, Zhejiang, Fujian, Guangdong, and Hainan
Central	Heilongjiang, Jilin, Henan, Shanxi, Anhui, Hubei, Hunan, and Jiangxi
Western	Gansu, Guizhou, Shaanxi, Yunnan, Xinjiang, Sichuan, Chongqing, Guangxi, and Inner Mongolia

2.2. Statistical analysis of inputs and outputs

The data show that the eastern region has a relatively high level of development, the backward development of the western region, and the unbalanced economic status of the three regions. The unbalanced regional development relates to university innovation and industrial research innovation. The average input and output values in the eastern region are higher than those in the western region in the R&D innovation stage of universities, 4.4 times and 2.6 times higher than those in the region, respectively. In the industrial R&D innovation stage, the average input and output in the eastern region are 6.8 times and 8.4 times higher than those in the western region respectively. From the most values of each indicator in the three regions, the maximum value of indicators in the eastern region is always the highest, while the western region is always the lowest. In the university innovation stage, the maximum input indicators of the central and the western regions are approximately the same, while in the output indicator of school R&D projects, the central region is 1.2 times that of the western region. In the industrial innovation stage, the maximum input index in the central region is 1.6 times that of the western region, but in terms of output it is 1.7 times that of the western region. This shows that the resources in the central region should always be better than those in the western region, no matter in the innovation stage of universities or industrial enterprises, which closely relates to the geographical location and economic environment of the western region.

From the standard deviation of input-output indicators from 2015 to 2019, the corresponding value of the eastern region is always the largest. Combined with the previous values, the eastern region has a relatively large investment in the university and industrial innovation phase, but there is a heterogeneity within the region.. In the stage of R&D and innovation in universities, the standard deviation of the western region is greater than that of the central region; the industrial stage is on the contrary. See Table 3 for details.

Table 3. Descriptive statistics of inputs and outputs

Cluster	Variable	Mean	Max	Min	Std.
Eastern	R&D personnel of universities	16765.8	5923	2	1397.89
	R&D internal expenditure of universities	10037343	3521348	327	854653
	School R&D projects	41993	15697	5	3461.22
	Academic and international exchange papers	537602	114444	2297	32885.13
	R&D personnel of industrial enterprises	2013204	642490	1779	182447.7
	R&D internal expenditure of industrial enterprises	83465498	23148566	74815	6765136
	Number of new product projects of industrial enterprises	358474.6	146954	500	34060.62
	Industrial sales revenue and market turnover	1.41E+09	4.52E+08	1026575	1.15E+08
Central	R&D personnel of universities	7446.2	2741	198	636.73
	R&D internal expenditure of universities	3572811	1822839	59932	413358.9
	School R&D projects	17028.2	8839	324	2146.71
	Academic and international exchange papers	255796.4	68278	11403	14944.61
	R&D personnel of industrial enterprises	554957.6	140361	11124	44533.61
	R&D internal expenditure of industrial enterprises	23657806	6087153	575015	1903309
	Number of new product projects of industrial enterprises	82744.4	27734	1910	7099.6
	Industrial sales revenue and market turnover	4.12E+08	1.11E+08	6284309	33714877
Western	R&D personnel of universities	4638.4	1621	16	561.75
	R&D internal expenditure of universities	2272335	1540823	502	380770
	School R&D projects	14746.2	7665	25	2255.52
	Academic and international exchange papers	204212.2	65029	8765	17834.06
	R&D personnel of industrial enterprises	265436.8	78289	4698	21677.4
	R&D internal expenditure of industrial enterprises	12285952	3878572	366180	981174.9
	Number of new product projects of industrial enterprises	42548.8	17648	924	4066.54
	Industrial sales revenue and market turnover	1.72E+08	54237861	3996429	16636984

2.3. Results and analysis

2.3.1. Overall efficiency analysis

The total efficiency of the parallel DEA two stages of universities and industries (Figure 3) shows on the whole that the total efficiency of Beijing, Hainan, and Yunnan Province from 2015 to 2019 is 1. This means that the efficiency of R&D and innovation in universities and industries in these three provinces is the best, and that these provinces have formed a relatively close and efficient university-industry relationship. The local economic development speed, technological development level and geographical location also played a role. The total efficiency of most provinces presents an upward trend during 2015 to 2019, but the tall efficiency of Anhui, Gansu, Guangxi, Guizhou, Jiangsu, Tianjin, and Xinjiang exhibit a downward trend in 2015–2019. The efficiency of most provinces is 0.80–0.95, which indicates that most provinces generally perform well in R&D and innovation, but can still be further improved. The total efficiency of Anhui in 2015, 2016, and 2018 was 1, but there was a slight

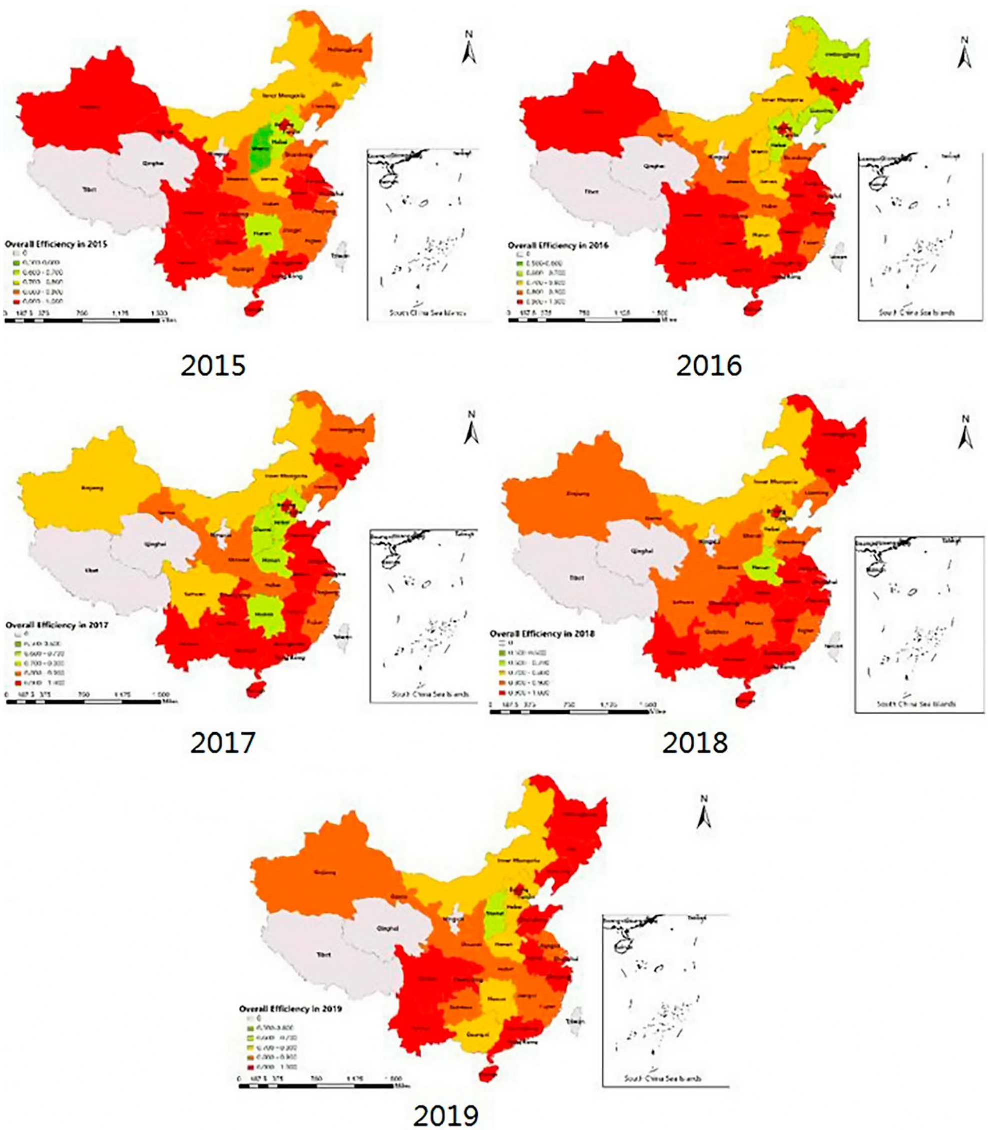

Figure 3. Temporal and spatial distributions of the total efficiency of China's provinces from 2015 to 2019

decrease in 2017 and 2019, indicating that Anhui has a relatively high efficiency in R&D and innovation from 2015 to 2019, but lacks stability. The efficiency value of Guangdong was 0.97 only in 2015, while the remaining efficiency values of 2016–2019 were all 1. This shows that the efficiency of Guangdong's industrial R&D innovation in colleges and universities has risen rapidly and can continue to be maintained at the optimal level. The efficiency values of Guizhou and Jiangsu were both 1 in 2015–2017 and dropped to around 0.9 in 2018 and 2019. Xinjiang also dropped from the efficiency frontier in 2015 and 2016 to around 0.8 in 2017–2019. In 2018 and 2019, the total efficiency of Guizhou and Jiangsu declined. In 2017–2019, the total efficiency of Xinjiang decreased, reflecting that the over level of local R&D and innovation is declining.

The overall efficiency averages for the three regions of China from 2015 to 2019 are shown in Table 4. In 2015 and 2016, the Eastern region lagged behind the Western region in terms of overall efficiency, but rebounded in the subsequent years 2017 to 2019. The efficiency values of the eastern and western regions have been around 0.9 in the past five years. Among them, the efficiency value of the eastern region is on the rise, and there the western region shows a downward trend. The efficiency value of the central region only exceeded 0.9 in 2018, while the efficiency of the remaining years fluctuated up and down. The central region needs to strengthen technological research and innovation.

Figure 4 depicts the overall efficiency values in Table 4. As the figure shows, the efficiency has increased in the East and Central regions, while the opposite is true for the West region. Specifically, since 2015, the gap between the overall efficiency values of the three regions has been narrowing, and the changes in the eastern region are relatively small. The overall efficiency of the western region declined in 2016–2017, then rebounded to a small extent, still lower than the efficiency value in 2015.

Table 4. Overall efficiency for 2015–2019 of three regions

Region	2015	2016	2017	2018	2019
Eastern	0.8885	0.8800	0.9312	0.9037	0.9103
Central	0.7908	0.8763	0.8498	0.9028	0.8565
Western	0.9460	0.9250	0.8620	0.8826	0.8932

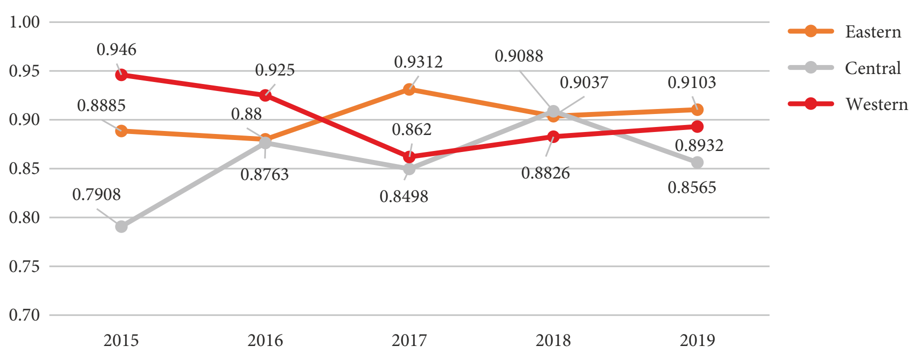

Figure 4. Trend of overall efficiency (2015–2019)

2.3.2. Efficiency analysis of university innovation stage

Figure 5 shows the efficiency of the R&D innovation phase of universities in China by province and city from 2015–2019. The innovation efficiency of universities in the central region is the lowest among the three regions. In the eastern region, the innovation efficiency value of universities in Beijing, Hainan, Jiangsu, and Shandong is 1 in 2015–2019, which relates to the large number of local colleges and universities, superior geographic location, and economic development. Hebei and Zhejiang provinces did not reach the efficiency frontier surface in 2015–2019 and had lower efficiency values in most years. Their local governments need to find out what shortcomings still exist in the local university innovation stage and resolve them. In addition, Tianjin's efficiency value was 1 in 2015–2017, but it fell to about 0.4 in 2018 and 2019. This indicates that the level of innovation in the province is unstable and the reasons behind the sharp decrease in efficiency need to be explored. From 2015 to 2019, Gansu, Guizhou, Inner Mongolia, Shaanxi and Yunnan were all at the frontier of efficiency in the western region. Other provinces also have excellent efficiency performance. Among them, Guangxi rose from 0.6 in 2015 to 1 in 2016–2018, but fell back to 0.6 in 2019. It shows that Guangxi has made great progress in the research and innovation of universities in the past five years, but it is still not stable enough. The university innovation stage in the western region performed well, indicating that the region has improved the level of technological R&D and innovation of local universities in recent years.

Anhui and Hubei are the two provinces in the central region that are at the forefront of innovation efficiency in universities from 2015–2019.Most other provinces have also reached the efficiency frontier in some years, indicating a high level of R&D innovation in regional universities, but with some fluctuations. Among them, the efficiency value of Henan from 2015 to 2019 did not reach 1. In 2016, its efficiency value reached more than 0.9, but the other years were less than 0.75. The number of colleges and universities in Henan is small, and colleges and universities are not innovative enough.

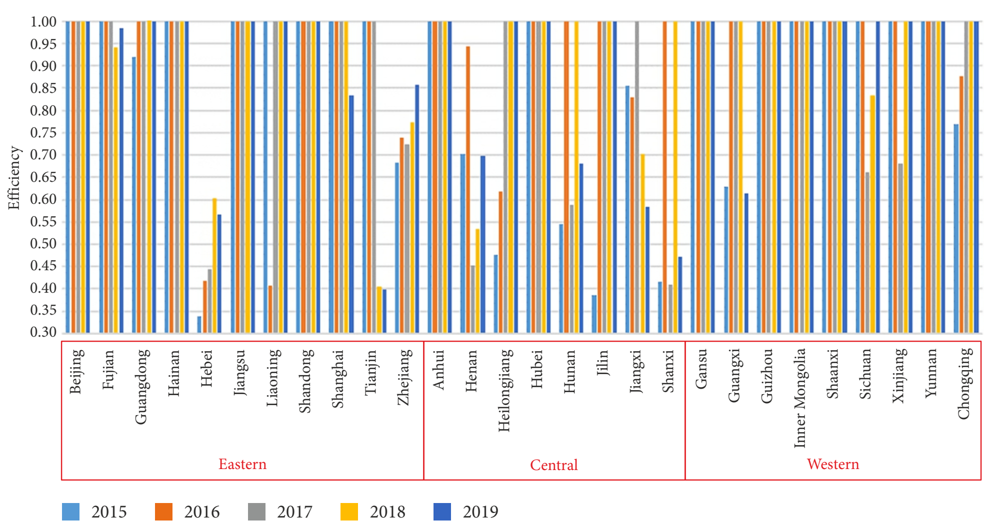

Figure 5. 2015–2019 China's regional university innovation efficiency trends

2.3.3. Efficiency of industrial innovation stage

Figure 6 shows the efficiency of the R&D innovation phase of industries in China by province and city from 2015–2019. Figure 6 shows the 2015–2019 industrial innovation efficiency value is 1 in Beijing, Guangdong, Hainan, Jiangsu, Zhejiang, Jilin, and Yunnan. In the past five years, the industries of various provinces have played a more important role in assuming social and economic responsibilities.

The eastern region has the most outstanding performance among the three regions, and nearly half of the provinces reach the efficiency frontier in this period. The efficiency of other provinces is on the rise. The efficiency of Fujian and Hubei in 2015–2019 were in the range of 0.5–0.6, which was lower than that of other provinces. The efficiency value of Shandong in 2017 reached 1, the rest of the years the efficiency values were below 0.8.

Compared with the eastern region, the central region has slightly lower industrial innovation efficiency in 2015–2019. Only Jilin Province has been at the forefront of efficiency. The efficiency value of Jiangxi Province in 2015 was 0.7, whereas the efficiency value of the remaining 4 years was 1. The efficiency value of Anhui in 2015, 2016, and 2018 was 1, while the efficiency value of the remaining years is between 0.8-0.1. Hubei only had an efficiency value of 1 in 2018, and the efficiency value for the remaining four years was only about 0.5. The efficiency values of Henan, Hunan, and Shanxi in 2015–2019 were all between 0.3–0.7. It shows that the three provinces need to make more efforts in industrial research and development of innovative technologies. From the western region, only Yunnan has an industrial innovation efficiency value of 1 in 2015–2019. The efficiency values of Xinjiang and Chongqing in 2015 and 2016 were all 1, but declined in 2017 to 2019. The efficiency value of Xinjiang dropped to about 0.5, and the efficiency of Chongqing also dropped below 0.8. The efficiency value of Guizhou from 2015 to 2017 was 1, and it fell to between 0.65–0.7 in 2018 and 2019. The efficiency of Gansu in 2015–2019 was between 0.4-0.8. From 2015–2019, the level of industrial innovation in Inner Mongolia, Shaanxi and Sichuan showed a slight upward trend.

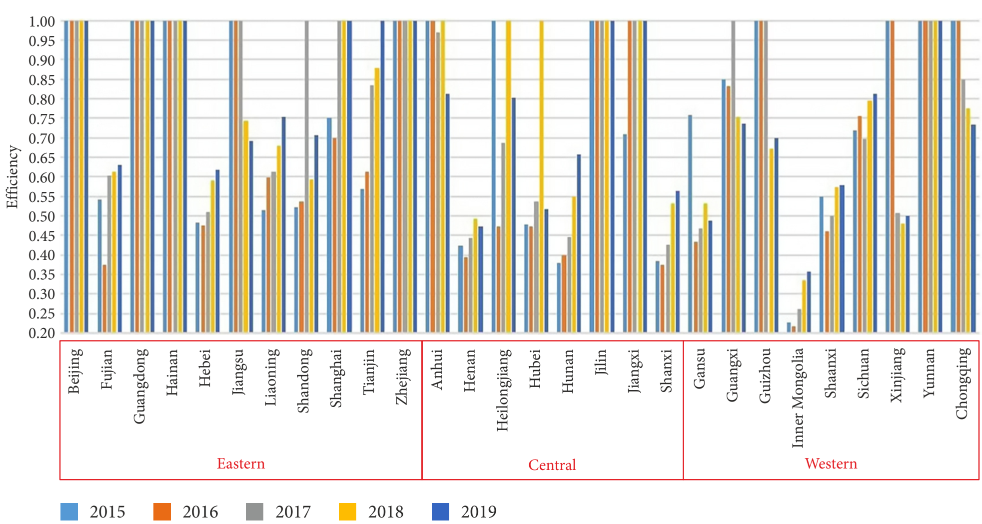

Figure 6. 2015–2019 China's regional industrial innovation efficiency

The efficiency level of Inner Mongolia and Shaanxi Province has remained below 0.4 and 0.6 in the past five years. This shows that the industrial innovation level of this region is lower than that of the other two regions.

2.3.4. Stage efficiency

Table 5 shows the total efficiency values for the parallel stages of universities and industries and the economic and environmental stages in three regions from 2015 to 2019. From Table 5 we see that the total efficiency of universities in the past five years is the highest.

The second stage is the economic and environmental stage. The provinces at the efficiency frontier in 2015–2019 include Beijing, Jiangsu, Tianjin, Zhejiang, Hubei, Hunan, Jilin, Guizhou, Sichuan, and Yunnan. In 2015–2019 the industrial R&D innovation stage was relatively backward in the total efficiency value of each stage. The provinces whose efficiency reached the frontier surface during the study period included a total of six provinces, including Beijing, Guangdong, and Hainan. From the perspective of the eastern region, from 2015 to 2019, only four provinces in the parallel R&D and innovation stage reached the efficiency frontier. The efficiency of other provinces in the industrial innovation stage is between 0.5–0.9. The efficiency value of each province in innovation stage of colleges and universities is between 0.45–1. On the whole, the total efficiency of the R&D and innovation stage of colleges and universities in the eastern region is better than that of the industrial innovation stage, and the efficiency value of the industrial innovation stage is closer to that of the economic and environmental stages. Therefore, industry in the eastern region has a greater impact on the economy and environment than colleges and universities. This may relate to the superior geographical conditions and relatively higher level of economic foundation in this region, creating good conditions for industrial innovation.

In the central region, only Jilin Province reached the efficiency frontier in the industrial innovation phase during the study period, and the frontier of efficiency in the innovation class of universities is Anhui Province and Hubei Province. The total efficiency of other provinces in the industrial R&D innovation stage in the past five years is between 0.4–1. In the innovation stage of universities, the total efficiency of other provinces is in 0.6–0.9 range in study period. On the whole, the total efficiency value of universities in this region in the past five years is higher than that of industry, and the efficiency value in the industrial innovation stage is closer to that in the economy and environment stage. Therefore, in the central region the impact of industry on the economic environment is greater. As for the western region, only Yunnan had a total efficiency value of 1 in the industrial innovation stage from 2015 to 2019, and the other provinces had a total efficiency value of 0.5–0.9. In the innovation stage of universities, the provinces with a total efficiency value of 1 include Gansu, Guizhou, Inner Mongolia, Shaanxi, and Yunnan, and the efficiency of other provinces are between 0.8–0.95. Industrial innovation in this region has a greater impact on economy and environment. Overall, industrial R&D innovation has a greater impact on economic and environmental stages than university R&D innovation in all three regions over the five-year period. Next, we further analyze the differences in the impact of university and industrial innovation on economic and environmental stages.

Table 5. Efficiency from 2015 to 2019 of the university innovation stage, enterprise innovation stage, and economic and environment stage

Region	DMU	University	Enterprise	Economic and Environment
Eastern	Beijing	1.0000	1.0000	1.0000
	Fujian	0.9850	0.5876	0.5142
	Guangdong	0.9839	1.0000	0.4898
	Hainan	1.0000	1.0000	0.8953
	Hebei	0.4740	0.5351	0.8515
	Jiangsu	1.0000	0.8871	1.0000
	Liaoning	0.8817	0.6324	0.5568
	Shandong	1.0000	0.6715	0.5020
	Shanghai	0.9665	0.8898	0.9053
	Tianjin	0.7607	0.7795	1.0000
	Zhejiang	0.7551	1.0000	1.0000
Central	Anhui	1.0000	0.9564	0.5732
	Henan	0.6669	0.4453	0.3045
	Heilongjiang	0.8186	0.7924	0.6074
	Hubei	1.0000	0.6010	1.0000
	Hunan	0.7629	0.4862	1.0000
	Jilin	0.8771	1.0000	1.0000
	Jiangxi	0.7941	0.9420	0.9655
	Shanxi	0.6599	0.4560	0.5279
Western	Gansu	1.0000	0.5360	0.6164
	Guangxi	0.8489	0.8341	0.8864
	Guizhou	1.0000	0.8744	1.0000
	Inner Mongolia	1.0000	0.2808	0.5633
	Shaanxi	1.0000	0.5327	0.4020
	Sichuan	0.8992	0.7554	1.0000
	Xinjiang	0.9363	0.6976	0.6428
	Yunnan	1.0000	1.0000	1.0000
	Chongqing	0.9289	0.8719	0.3797

The differences between the parallel phase efficiency values and the second phase and efficiency values for each province and city from 2015 to 2019 are shown in Table 6. In the table, Stage11 refers to the industrial innovation stage, and stage12 refers to the university innovation stage.

In 2015 from three regions, there were 7 provinces with a gap of 0 between the efficiency value of industrial R&D and innovation stage and the economic and environmental efficiency value: Jiangsu, Tianjin, Hubei, Hunan, Jilin, Guizhou, and Yunnan. The efficiency value difference of other provinces in 2015 was between 0.01–0.5. There are 5 provinces where the difference between efficiency value and economic and environmental efficiency in innovation stage of colleges and universities is 0: Tianjin, Hunan, Jiangxi, Guizhou, and Sichuan. The difference between efficiency values of other provinces is 0–0.57. By comparative analysis, we found that the industrial innovation of the year had a greater impact on the second stage t. This shows that industrial enterprise innovation is more closely related to the economy and environment this year.

Table 6. Efficiency difference between university stage, enterprise stage, and economic and environment stage from 2015 to 2019

Cluster	DMU	2015		2016		2017		2018		2019	
		Satge 11	Stage 12	Satge 11	Stage 12	Satge 11	Stage 12	Satge 11	Stage 12	Satge 11	Stage 12
Eastern	Beijing	0.290	0.556	0.328	0.437	0.293	0.437	0.327	0.555	0.410	0.375
	Fujian	0.156	0.223	0.166	0.319	0.007	0.092	0.489	0.000	0.215	0.107
	Guangdong	0.008	0.023	0.019	0.013	0.044	0.063	0.056	0.367	0.123	0.121
	Hainan	0.262	0.477	0.780	0.000	0.739	0.000	0.665	0.000	0.676	0.000
	Hebei	0.431	0.571	0.391	0.000	0.201	0.440	0.038	0.396	0.271	0.126
	Jiangsu	0.000	0.376	0.000	0.000	0.000	0.376	0.000	0.000	0.000	0.000
	Liaoning	0.150	0.134	0.137	0.016	0.081	0.011	0.104	0.000	0.093	0.118
	Shandong	0.215	0.200	0.119	0.233	0.028	0.162	0.012	0.164	0.459	0.055
	Shanghai	0.044	0.334	0.310	0.587	0.000	0.590	0.000	0.616	0.000	0.000
	Tianjin	0.000	0.000	0.023	0.000	0.109	0.572	0.126	0.467	0.350	0.000
	Zhejiang	0.322	0.166	0.000	0.175	0.000	0.000	0.000	0.528	0.000	0.466
Central	Anhui	0.215	0.175	0.025	0.171	0.023	0.036	0.056	0.045	0.035	0.160
	Henan	0.202	0.011	0.148	0.038	0.153	0.059	0.302	0.132	0.263	0.188
	Heilongjiang	0.137	0.043	0.199	0.016	0.145	0.138	0.160	0.107	0.304	0.087
	Hubei	0.000	0.238	0.000	0.143	0.187	0.000	0.273	0.000	0.333	0.000
	Hunan	0.000	0.000	0.000	0.000	0.000	0.005	0.000	0.581	0.000	0.340
	Jilin	0.000	0.347	0.000	0.282	0.000	0.307	0.000	0.267	0.000	0.243
	Jiangxi	0.471	0.000	0.548	0.000	0.576	0.000	0.504	0.000	0.363	0.172
	Shanxi	0.068	0.340	0.068	0.250	0.069	0.425	0.152	0.122	0.174	0.358
Western	Gansu	0.098	0.004	0.204	0.160	0.196	0.130	0.227	0.339	0.165	0.041
	Guangxi	0.251	0.568	0.301	0.000	0.474	0.000	0.431	0.000	0.438	0.000
	Guizhou	0.000	0.000	0.000	0.000	0.000	0.000	0.408	0.000	0.473	0.000
	Inner Mongolia	0.160	0.083	0.098	0.191	0.296	0.043	0.298	0.263	0.103	0.491
	Shaanxi	0.342	0.567	0.411	0.333	0.202	0.488	0.179	0.369	0.574	0.000
	Sichuang	0.465	0.000	0.460	0.000	0.463	0.000	0.473	0.080	0.483	0.035
	Xinjiang	0.140	0.149	0.183	0.068	0.186	0.028	0.137	0.402	0.006	0.105
	Yunnan	0.000	0.212	0.247	0.035	0.146	0.296	0.000	0.282	0.000	0.084
	Chongqing	0.014	0.236	0.089	0.292	0.519	0.083	0.455	0.536	0.422	0.500

In 2016, Jiangsu, Zhejiang, Hubei, Hunan, Jilin, and Guizhou had a difference of 0 between the efficiency of industrial innovation stage and economic and environmental stage inthree regions. The difference of efficiency between industrial R&D innovation stage and economic and environmental stage in other provinces is between 0.01–0.55. In the R&D and innovation stage of colleges and universities, the efficiency value difference of Hainan, Hebei, Jiangsu, Tianjin, Hunan Province, Jiangxi, Guangxi, Guizhou, and Sichuan is 0. The efficiency range of other provinces at this stage is 0.01–0.6. Through a comparison, we see that the R&D and innovation of colleges and universities had a greater impact on the second stage in 2016, which may relate to the high level of innovation of Chinese colleges and universities in that year and the good effect of linkage and cooperation between colleges and universities and the economy and environment.

In 2017, Jiangsu, Shanghai, Zhejiang, Hunan, Jilin, and Guizhou had an efficiency difference of 0, while the efficiency difference of industrial innovation stage in other provinces was generally between 0–0.55. In the innovation stage of universities, seven provinces had an efficiency value difference of 0: Hainan, Zhejiang, Hubei, Jiangxi, Guangxi, Guizhou, and Sichuan. Except for the provinces with a difference of 0, the difference of innovation efficiency of colleges and universities in other provinces is between 0.02–0.6. Therefore, the economy and environment are more affected by university R&D innovation in 2018. In 2018, Jiangsu, Shanghai, Zhejiang, Hunan, and Jilin had an efficiency value difference of 0 in the industrial R&D and innovation stage of three regions, while most of the other provinces were in 0.01–0.5 range. In the R&D and innovation stage of colleges and universities, the efficiency value difference of 0 covers Fujian, Hainan, Jiangsu, Liaoning, Hubei, Jiangxi, Guangxi, and Guizhou, and the efficiency value difference of the other provinces was generally between 0.01–0.6. Overall, although there are more provinces with a difference of 0 between the innovation stage of colleges and universities and the economic and environmental stage. On the whole, the efficiency difference between the industrial R&D and innovation stage and the economic and environmental stage is smaller. Therefore, the economy and environment are more affected by industrial R&D innovation in 2018.

In 2019 Jiangsu, Shanghai, Zhejiang, Hunan, Jilin, and Yunnan had an efficiency difference of 0 between the industrial innovation stage and the economic and environmental stage in three regions, the efficiency value difference of other provinces is between 0–0.7. There are 8 provinces in which the difference between the efficiency value of university innovation stage and the efficiency value of economic and environmental stage is 0: Hainan, Jiangsu, Shanghai, Tianjin, Hubei, Guangxi, Guizhou, and Shaanxi. In addition, the efficiency value difference of university innovation stage in other provinces is between 0.03–0.5. We see in 2019 that colleges and universities had a greater impact. By analyzing the efficiency value difference of the two stages of each year from 2015 to 2019, we conclude that the years in which industrial R&D innovation had a greater impact on the second stage are 2015 and 2018, and the remaining years in 2016, 2017, and 2019 are when university R&D innovation had a greater impact on the second stage. Combined with the analysis results in Table 5 above, industrial R&D and innovation have a great impact on the economy and environment. Therefore, we conclude that the impact of the university innovation stage is limited, although it is more significant in more years than the industrial innovation stage. When universities are less efficient in linking with the economy and the environment than industrial firms, it may result in a greater economic and environmental impact of industrial innovation, which is the result of the analysis in this study.

In 2020, China ranked second in the world in R&D investment with 2.439 trillion yuan. This study compares and analyzes the impact of university R&D innovation stage and industrial R&D innovation stage on the economy and environment, which can provide suggestions and references for the investment allocation of research and experimental development funds in China. Efficiency is not the only criterion for allocation, and in future allocation of research funds, care should be taken to avoid a one-sided bias in favor of efficient departments. While scientific research funds are properly inclined to industrial R&D and innovation, local governments should also continue to develop the R&D and innovation strength of universities, improve the up-down linkage between colleges and universities and the economy and environment, and further improve its impact on the economic environment.

2.3.5. Efficiency analysis of economic and environment stage

The second phase is based on the parallel phase of R&D innovation unfolding and the efficiency assessment of environmental and economic efficiency through linked variables combined with energy inputs. Combining the link variable of universities and enterprises with energy consumption can not only study the impact of R&D innovation of universities and enterprises on the environment and economy, but also echo the importance of R&D cooperation between universities and industries mentioned in the introduction above, which can reflect whether the innovation linkage between universities and enterprises is close to a certain extent. In the economic and environmental stage, the total output efficiency of the three regions is arranged in the order of east, west and middle respectively. Among them, he total output efficiency of nine provinces including Anhui, Beijing, Fujian and Gansu in the economic and environmental stages from 2015 to 2019 is 1illustrating that the innovation activities of the above provinces in the parallel stage have a relatively positive impact on the economy and environment. To a certain extent, they reflect a certain degree of linkage and cooperation between their R&D innovation, so the innovation efficiency is high.

The total output efficiency level of the provinces and cities in the eastern region is in a good trend, and most of them are at the frontier or on an upward trend. Among them, Guangdong Province and Hainan Province have shown a downward trend in the past five years, but the magnitude is not large, at about 0.1; the efficiency value of Guangdong Province in the past five years are less than 0.4, indicating that the R&D and innovation activities of universities and enterprises in this province have little contribution to the economic and environment. The total output efficiency of Shandong increased from 0.21 in 2015 to 1 in 2018, and then fell to 0.68, indicating that the province has the potential to improve efficiency but is still not stable enough.

In the central region, those provinces that are not on the efficiency frontier have an overall upward trend in efficiency. Among them, the total output efficiency of Jiangxi in the past five years is roughly in the range of 0.4–0.7, which has the largest room for improvement compared with other provinces in the central region. In addition, Henan Province and Shanxi Province need to be mentioned. The total output efficiency value of Henan Province from

2015 to 2017 was 1, and then decreased to about 0.5 in the following two years, which shows that the universities in the region were closely connected with industry in the early five years, and the total output capacity in the economic and environmental stages was strong, but still not stable; Although the efficiency value of Shanxi Province has been rising, the efficiency value in the first four years is less than 0.5. In summary, certain measures still need to be taken by the region to make innovation in universities and industrial enterprises better serve economic and environmental development.

The trend of total output efficiency in the economic and environmental stage of the western region was optimistic during the study period. Only Guizhou province's total output efficiency fluctuated and declined, from 0.54 in 2015 to 0.23 in 2019. Among the growing provinces, Sichuan province and Yunnan province had the most obvious growth in total output efficiency, with Sichuan's efficiency value less than 0.5 in 2015 and efficiency on the frontier in the last four years; Yunnan province had a low efficiency level of less than 0.3 in the first four years, and jumped to 1 in 2019.

This shows that the contribution of R&D innovation of universities and enterprises to the social economy and environment is not high in this region in recent years. For this phenomenon, the local should actively analyze the reasons behind the efficiency growth to prevent the efficiency from falling back. Table 7 presents the details.

Table 7. Total output efficiency of each province from 2015 to 2019

DMU	2015	2016	2017	2018	2019
Anhui	1.0000	1.0000	1.0000	1.0000	1.0000
Beijing	1.0000	1.0000	1.0000	1.0000	1.0000
Fujian	1.0000	1.0000	1.0000	1.0000	1.0000
Gansu	1.0000	1.0000	1.0000	1.0000	1.0000
Guangdong	0.3267	0.3202	0.3136	0.2897	0.2721
Guangxi	0.4994	0.6825	0.5641	0.5597	0.5605
Guizhou	0.5446	0.6029	0.2759	0.2420	0.2332
Hainan	0.5298	0.5179	0.5380	0.4542	0.4090
Hebei	1.0000	1.0000	1.0000	1.0000	1.0000
Henan	1.0000	1.0000	1.0000	0.7393	0.5184
Heilongjiang	1.0000	1.0000	1.0000	1.0000	1.0000
Hubei	1.0000	1.0000	1.0000	1.0000	1.0000
Hunan	0.5726	0.5936	0.5526	0.6154	0.7027
Jilin	0.4294	0.5582	0.3791	0.6742	0.7756
Jiangsu	0.4245	0.5437	0.4257	0.6537	0.5916
Jiangxi	0.4818	0.6079	0.6046	0.7196	0.6684
Liaoning	0.6490	0.8776	1.0000	1.0000	1.0000
Inner Mongolia	1.0000	1.0000	1.0000	1.0000	1.0000
Shandong	0.2125	0.1979	0.4816	1.0000	0.6793
Shanxi	0.3387	0.3724	0.4721	0.4561	0.8706

End of Table 7

DMU	2015	2016	2017	2018	2019
Shaanxi	0.6508	0.6296	0.6567	0.5985	0.6782
Shanghai	0.4321	1.0000	1.0000	1.0000	1.0000
Sichuan	0.4764	1.0000	1.0000	1.0000	1.0000
Tianjin	1.0000	1.0000	1.0000	1.0000	0.8276
Xinjiang	0.4946	0.5312	0.5375	0.5863	0.6343
Yunnan	0.2575	0.2520	0.2670	0.2335	1.0000
Zhejiang	1.0000	1.0000	1.0000	1.0000	1.0000
Chongqing	1.0000	1.0000	1.0000	1.0000	1.0000

2.3.6. Input variables' efficiency analysis

Most of the provinces have high efficiency values for the input indicators of the R&D and innovation stages. Among them, three provinces have an efficiency value of 1 for all input terms in the R&D innovation stage, and most of the rest are above 0.8, indicating that the input resources are more fully utilized in the parallel stage. The average value of the efficiency of energy consumption shows, Hunan and Tianjin did not reach 0.5, but the average efficiency value of energy consumption in most other provinces reached more than 0.6. Half of the provinces hit more than 0.9, indicating the good overall utilization of energy.

In the university innovation stage, the efficiency value of the investment indicator for R&D personnel of universities is high at between 0.82–1. It shows that universities in various provinces actively recruit excellent scientific researchers and reasonably match their own resources, which makes this indicator more efficient. In terms of internal expenditure efficiency of university R&D, most provinces have excellent performance, and the corresponding efficiency value is above 0.9, which shows that the scientific research funds of colleges and universities are relatively sufficient, and the government and industry support the funds of colleges and universities greatly. With sufficient funding for scientific research, colleges and universities recruit scientific research talents to further improve innovation level.

In the industrial innovation stage, the efficiency performance of industrial enterprises' R&D personnel input index is relatively excellent, with efficiency values mostly above 0.8. Most provinces in the eastern and central regions have an efficiency value of 1, indicating that the efficiency of R&D personnel is relatively high, which relates to the scale of local scientific research personnel. Moreover, the efficiency of R&D personnel in the eastern and central regions is higher than that in the western regions, which means the researchers in the western region have a greater distance from the efficiency frontier. Therefore, the government should take corresponding measures to reduce regional differences. From the R&D internal expenditure, the efficiency value of most provinces is above 0.7. Among them, the efficiency of Inner Mongolia, Shandong, Hebei, and Fujian are lower than 0.65. Local governments should increase supervision over industrial research funding and reduce inefficient capital investment. Table 8 lists the details.

Table 8. Average input efficiency by province

DMU	Industrial employees	Industrial R&D funds	School researchers	Schools' R&D funds	Energy consumption
Anhui	1.0000	0.9620	1.0000	1.0000	1.0000
Beijing	1.0000	1.0000	1.0000	1.0000	0.6038
Fujian	0.6702	0.5440	0.9940	1.0000	0.6991
Gansu	0.8475	0.6747	1.0000	1.0000	0.9241
Guangdong	1.0000	1.0000	0.9917	1.0000	0.9291
Guangxi	1.0000	0.9206	0.8272	0.9414	1.0000
Guizhou	0.8894	0.8722	1.0000	1.0000	0.7391
Hainan	1.0000	1.0000	1.0000	1.0000	0.6527
Hebei	0.8861	0.6233	0.8733	0.7452	0.9850
Henan	0.8343	0.6965	0.8792	0.9380	1.0000
Heilongjiang	0.8170	0.8258	1.0000	0.9064	1.0000
Hubei	1.0000	0.7871	1.0000	1.0000	0.8494
Hunan	1.0000	0.7736	0.8318	0.9469	0.4717
Jilin	1.0000	1.0000	0.9153	1.0000	0.8254
Jiangsu	0.9913	0.8871	1.0000	1.0000	1.0000
Jiangxi	1.0000	0.9311	0.8292	0.9281	1.0000
Liaoning	1.0000	0.7403	1.0000	0.9090	1.0000
Inner Mongolia	0.7179	0.4314	1.0000	1.0000	0.9973
Shandong	1.0000	0.6335	1.0000	1.0000	0.7232
Shanxi	0.8249	0.7061	0.8269	0.9101	0.7982
Shaanxi	0.9083	0.7511	1.0000	1.0000	0.9251
Shanghai	1.0000	0.9058	0.9671	1.0000	1.0000
Sichuang	0.8983	0.7598	0.9855	1.0000	0.7041
Tianjin	1.0000	0.9045	0.9891	0.8796	0.4769
Xinjiang	0.9918	0.7431	1.0000	0.9186	1.0000
Yunnan	1.0000	1.0000	1.0000	1.0000	0.8349
Zhejiang	1.0000	1.0000	0.8643	0.9091	1.0000
Chongqing	1.0000	0.8224	0.9261	0.9867	0.5249

Discussion and conclusions

This study measures the stage efficiency of university innovation stage and industrial innovation stage in 28 Chinese provinces from 2015 to 2019 respectively, as well as the efficiency of the economic and environmental stages of their combination. It was found that the efficiency of these two parallel stages was very different and had an impact on the overall efficiency of their combination. All provinces and cities have potential for progress in R&D and innovation, and face the common challenge of achieving harmonious economic and environmental development. Therefore, provincial and municipal governments should formulate development policies based on local economic characteristics. We summarize the efficiency of input-output indicators with the conclusion as follows.

1. Based on the performance of the efficiency in Stage II, the Eastern region did not consistently maintain optimal efficiency, and the western region has not always been lagging behind. From 2015 to 2016, the overall efficiency value of the western region is in the leading position; from 2017 to 2019, the leading region becomes the eastern region. The differences in the efficiency of R&D and innovation among universities, industry, environment, and economy relate to the regional economic development level, industrial composition, and geographic environment. The government should help the inefficient areas recruit highly-qualified personnel and raise the level of industrial technology research and innovation. At the same time, the authorities should strongly support and actively guide the flow of social funds into the corresponding provinces in R&D and innovation's aspects to help improve the level of efficiency.
2. In the university innovation stage, most provinces have excellent efficiency performance, with many provinces having an efficiency value of 1; however, at the same time, in the industrial innovation stage, provinces are relatively lagging behind in efficiency performance. The differences between China's three regions are due to the following reasons. First, the economic development of the three regions is unbalanced. Economic foundation is a prerequisite for the progress of industrial technology, and the imbalance in economic foundation between regions has to a certain extent caused the imbalance in the development of industrial technology level. Second, the distribution of highly qualified technical personnel is uneven. The disparity in economic foundation and benefits of each region together causes frequent cross-regional mobility of talent, so it may be that the more in the region where efficiency needs to be developed, the less highly qualified talent there is. Third, the government must ensure the integrity of the existing industrial R&D and innovation technology chain when carrying out industrial reforms to replace enterprises.
3. Universities in three regions of China all have superior innovation efficiency performance. This shows from 2015 to 2019 that colleges and universities have assumed the responsibility of social education, scientific research, and innovation, and the effect of cooperation with industry is also strong. The organic combination of production, education and R&D departments should be paid attention to by relevant departments, so as to cultivate multi-directional high-quality talents.
4. In terms of the effects of the parallel stage of university and industry on economic and environmental stages, the effects of industrial innovation stage on economic and environmental stages was more pronounced in all three major regions of China from 2015 to 2019. This reflects the poor linkage effect between university research and innovation and economy and environment and the impact on local economic and environmental development is not significant. Therefore, industry should be guided to actively and deeply cooperate with colleges and universities, improve industrial R&D efficiency, reduce corresponding energy consumption, and serve the sustainable development of the local social environment.

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