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Data-Driven Evaluation of Regional Innovation Capability:
A Case Study of Anhui Province

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ABSTRACT

Regional innovation capability is considered an important driving force for the sustainable and high-quality development of regional economy. Therefore, data-driven evaluation method of regional innovation capability is proposed. First, the article collects regional innovation development statistics; second, min-max standardization method is used for dimensionless data processing, and anti-entropy method is used to calculate index weight; third, a composite system synergy degree model for objective and quantitative evaluation is built; finally, using Anhui Province as an example, the feasibility of the method was verified . The results indicate that the order and synergy degree of the innovation input and innovation output subsystems of Anhui Province have shown an upward trend from 2010 to 2019. However, innovation output has not been synchronized with innovation input. Therefore, suggestions for improving Anhui's regional innovation capability are proposed. This study provides theoretical and methodological support for evaluating and optimizing regional innovation capability.

KEYWORDS

Anhui Province, Anti-Entropy Method, Composite System Synergy Degree Model, Data-Driven, Input-Output, Min-Max Standardization Method, Regional Innovation Capability, Sustainable Development

INTRODUCTION

With the rapid development of the global economy, the contradiction between the economic development mode driven by factors and investment and the gradual depletion of resources and the environment has become increasingly prominent. To achieve the sustainable development of the

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economy and society, it is important to understand the transformation from economic development mode to innovation-driven mode (Geng et al., 2019). The innovation-driven model can effectively solve the problems caused by the limited carrying capacity of resources and the environment (Song et al., 2019), reduce the pressure of resources in economic development, improve the efficiency of resource utilization, and promote sustainable development of the economy. Studies have indicated that the innovation-driven mode can cause a significant increase in total factor productivity and economic aggregate. Every 1% increase in the stock of science and technology capital will result in a growth of 0.05-0.1 in the economic aggregate, and its social rate of return is approximately 20–50% (Cameron & Quinn, 1998). Through practice, the contribution rate of innovation to the economy has increased from approximately 5% at the beginning of the last century to more than 50% in the 1950s-1970s, and since the 1990s, the contribution rate to some developed countries is more than 80%. In particular, since the beginning of the new century, a series of actions from the national innovation strategy of the United States, the 2020 strategic innovation plan of the European Union, the industrial 2050 strategy of the United Kingdom, to the national innovation-driven development strategy outline of China indicate that the innovation-driven mode is increasingly becoming a new channel for global economic growth. As the main battlefield of national economic development, a region undertakes the important mission of implementing an innovation-driven development strategy. To achieve regional innovation-driven development, the most fundamental is to enhance regional innovation capability. Regional innovation capability is the embodiment of the continuous optimization of a regional innovation system structure and the continuous exertion of an innovation function. It is the key factor affecting regional economic growth and an important reference index to measure the economic strength and comprehensive competitiveness of a country or region. Accurately measuring, evaluating, and optimizing regional innovation capability has become a challenge for global sustainable development.

The concept of regional innovation capability was first proposed by Cooke (1998), who defined it as “the ability to successfully use new knowledge”. There is no consensus in the academic circles on the concept of regional innovation capability. Shan (2017) defined the concept of regional innovation capability as “within a certain space, the innovation subject’s comprehensive ability to allocate regional innovation output resources and strengthen regional economic strength,” and divided the constituent elements of regional innovation capability into four aspects: input capability, innovation environment, management capability, and innovation output. Fu et al. (2020) pointed out that regional innovation capability refers to creating new technological ideas by effectively allocating innovation resources and transforming them into new products or services to achieve regional growth. Park et al. (2021) believes that the regional organizations constituting the regional innovation system will carry out various innovation related activities and bring new products and services based on new technologies and processes to the market. The novelty of their activity results is of significance to measure the regional innovation capability. Within the definition of these concepts, the generally accepted concept is that regional innovation capability is an innovation potential of a specific region that can continuously develop innovations related to business, and it is the adaptability of a regional innovation subject to environmental change and the utilization ability of existing resources in innovation activities (Tura & Harmaakorpi, 2005). This paper defines the connotation of regional innovation capability as the capability of a region to transform knowledge into new products, new processes, and new services in combination with its own resource endowments such as communication, culture, market, economy, and education. Its core objective is to promote the interaction and resource integration among innovation subjects (including government, enterprises, education departments, scientific research institutions, and intermediary service institutions) (Coombs et al., 2019), which is manifested in the capability to contribute to the regional social and economic system. Regional innovation capability is regarded as the decisive factor for a regional economy to obtain a unique competitive advantage (Foss, 1996; Piazza et al., 2019), and it is also an important factor to solve the regional economic prosperity difference (Romijn & Albu, 2002; Tian & Wang, 2018; Xiao et al., 2019). Studies indicate that regional innovation capacity has a great potential to improve the quality of economic development (Geng et al., 2019; Song et al., 2019).

Regarding the evaluation index and measurement of regional innovation capability, scholars construct the index system according to the constituent elements of regional innovation capability and draw lessons from OECD's Oslo manual, EU's European Innovation rankings, US's 21st-century innovation working-group report, and China's regional innovation capability report to depict various indicators of innovation capability. Additionally, they construct the evaluation index system of regional innovation capability from the perspectives of input-output (Asheim & Isaksen, 2002), direct-indirect (Nizar et al., 2005), knowledge management(Chen & Wang, 2012), green and low-carbon (Wang et al., 2017), university-industry (Rantala & Ukko, 2019), and technology orientation (Park et al., 2021). Although these studies have different perspectives, there is still some consensus on some indicators. Innovation resources, innovation output, and innovation environment (Buesa et al., 2006; Zhao et al., 2015; Shan, 2017) is a common index when constructing the evaluation index system of regional innovation capability. Scholars have adopted patents (Quatraro,2009; Sleuwaegen & Boiardi, 2014; Xu & Zhai, 2020) successively as an important indicator of regional innovation output. Furthermore, according to the operation mechanism of regional innovation capability, some scholars have constructed the evaluation index system of regional ecological innovation capability from the four elements of internal environment, strategy, operation, and structure (Ceptureanu et al., 2020).

Regarding the evaluation and optimization of regional innovation capability, factor analysis (Polina & Solovyeva, 2019), PCA (Pinto & Guerreiro, 2010), DEA (Zabala-Iturriagagoitia et al., 2007; Xu et al., 2020), and AHP (Zhao et al., 2013; Wang, 2017; Heindl & Liefner, 2019) are the most widely used evaluation methods. Moreover, studies have discussed the applications of logical equation (Quartararo, 2009), social network analysis (Prevezer et al., 2013), BP neural network (Gao, 2014), the multi-dimensional grey fuzzy decision-making pattern (Li et al., 2016), and the multiple attribute decision-making method (Su et al., 2020) in regional innovation capability evaluation. Regarding the optimization of regional innovation capability, based on the regional characteristics (Billon et al., 2017), scholars optimize regional innovation capability regarding the efficiency of green technology manufacturing (Fu et al., 2020), financial and tax policy regulation (Qi et al., 2020; Song et al., 2020), building regional open innovation roadmap (Schwerdtner et al., 2015), innovation subjects (Zhao et al., 2013; Su & Sun, 2018), government quality (Rodriguez-Pose & Di Cataldo, 2015), and intelligent specialization (Kogut-Jaworska & Ociepa-Kicińska, 2020).

Based on the analysis of these research results, the research status and limitations in this field are as follows. First, from the perspective of the evaluation index, considering the regional heterogeneity (Ganau & Grandinetti, 2021), the evaluation indexes of regional innovation capability are different. Moreover, there are inevitably subjective errors in the quantification of qualitative indexes when collecting existing evaluation indexes of regional innovation capability. Therefore, a deep insight into the objective data of regional innovation based on data-driven, mining quantitative indexes to ensure the objectivity, accuracy, and persuasiveness of the evaluation is necessary. Second, from the perspective of evaluation methods, scholars use more evaluation methods, such as factor analysis, PCA, AHP, and so on. There are few types of research on how to use objective data for quantitative evaluation. Third, from the perspective of optimization countermeasures, the existing research results mostly propose countermeasures from three aspects: innovation subject, innovation resources, and innovation environment. There are few countermeasures to enhance regional innovation capability oriented by collaborative innovation. Therefore, to overcome the above limitations, this study proposes a data-driven evaluation method of regional innovation capability, which can quantitatively evaluate the regional innovation capability, have a clear understanding of the development trend and law of regional innovation capability, and thus accurately position the cultivation of innovation capability.

The research has theoretical and practical significance. The theoretical significance is as follows. Under the premise that the evaluation indexes of regional innovation capability have not been unified, based on the availability and effectiveness of data, the evaluation indexes of regional innovation capability are constructed from the perspective of an input-output subsystem, which provides a new research perspective for evaluating innovation capability. The evaluation model of regional innovation capability is constructed from the perspective of coordination, and thus the quantitative evaluation of regional innovation capability is realized from the subsystem and the composite system. The comprehensive evaluation mechanism of "measurable, evaluable, and optimized" of regional innovation capability based on data-driven is constructed, which enriches the evaluation model of regional innovation capability. The practical significance is as follows. This study can help the government and enterprises to understand the level of regional innovation capability comprehensively and objectively based on the perspective of an input-output subsystem, to discover the obstacles that affect the development of regional innovation capability, and explore the key factors affecting innovation input and output, and seek effective solutions and upgrading paths. Thus, through a data-driven evaluation method, we can solve the bottleneck that restricts the development of regional innovation, and make innovation-driven development strategy the booster of regional and national economic development. The countermeasures to improve the regional innovation capability provided by this study are significant for the improvement of the regional innovation level and the realization of high-quality economic development.

Using Anhui Province as the research object, this study examines the regional innovation capability from the perspective of synergy through the composite system synergy degree model. From the perspective of an input-output subsystem, it constructs the evaluation indexes of Anhui regional innovation capability and evaluates the regional innovation capability by sorting out and calculating the basic data of Anhui Province from 2009 to 2019. To achieve the research objectives, the framework of this study is as follows: Section 2 contains the method, mainly introducing the data collection, data processing, and data modeling. Section 3 uses Anhui Province as an example to evaluate the regional innovation capability, verify the effectiveness and feasibility of the method, and thus propose the optimization countermeasures. Section 4 is the conclusion.

METHOD

This study aims to improve regional innovation capability, and based on determining the research scope and research purpose, conducts data collection, data processing through min-max standardization method and anti-entropy weight method, and uses the composite system synergy degree model for data modeling, and thus integrates the effective information to the regional decision-makers for reference. This section is a comprehensive introduction of the data-driven innovation capability evaluation method, which is elaborated according to the logical main line of method framework, data collection, data processing, and data modeling.

Method Framework

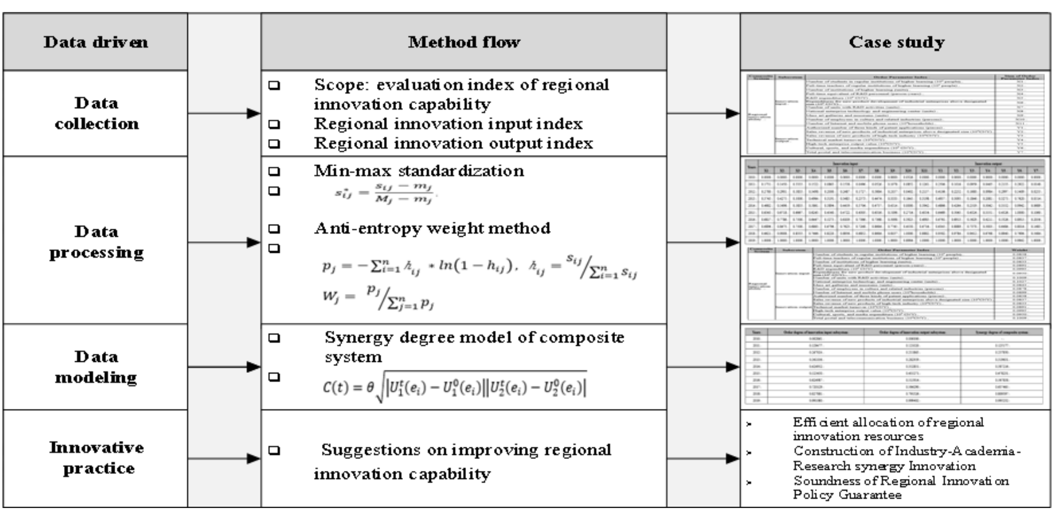
This study divides the regional innovation composite system into regional innovation input subsystem and regional innovation output subsystem and constructs a data-driven innovation capability evaluation method to measure, evaluate, and optimize the regional innovation capability. To ensure the objectivity of the data, the data collected include the data of the refined factor indexes of the regional innovation input and output subsystem. In data processing, the min-max standardization method is used to process the original data dimensionless and standardized, and the anti-entropy method is used to measure the index weight in the regional innovation input and output data subsystem. Data modeling is based on the composite system synergy degree mode to study the relationship between the elements of each subsystem and regional innovation capability, and calculate the order degree of each subsystem and the overall synergy degree of the innovation composite system. Finally, the evaluation method is applied to the Anhui case for verification, and the evaluation results and countermeasure suggestions are obtained. The data-driven evaluation method of innovation capability provides method support for the evaluation of regional innovation capability and theoretical policy support for improving resource utilization efficiency (Xu, et al., 2018; Peng et al.,2020) and promoting the high-quality development of regional innovation. The method flow is presented in Figure 1.

Data Collection

Based on the measurement scale introduced by relevant scholars (Shan, 2017; Su et al., 2020; Xu et al., 2020), the data collection indicators in this paper focus on the measurement of regional innovation capability to evaluate the input and output of regional innovation processes, mainly because these are relatively easy to quantify and measure (Asheim and Isaksen, 2002). Further, some databases such as the China Statistical Yearbook, Anhui statistical yearbook, and China Science and Technology statistical yearbook can retrieve the required data efficiently and at a low cost. The connotation of regional innovation capability defined in this paper agrees with the assertion that regional innovation capability is the result of the interaction of regional culture, society, and economy (Buesa et al., 2006; Zhao et al., 2013). Therefore, in the construction of the measurement scale, this paper fully considers the indicators of culture, society, and economy in regional innovation input and innovation output. At the same time, the connotation of regional innovation capability defined in this paper agrees with the point that the regional innovation subjects involve the government, enterprises, education departments, scientific research institutions, and intermediary service institutions (Su et al., 2020; Heindl & Liefner, 2019). Therefore, in the construction of the measurement scale, the index system of regional innovation subjects in regional innovation input and innovation output is also fully considered.

Using the regional innovation capability as the research object, this study divides the regional innovation composite system into regional innovation input subsystem and regional innovation output subsystem. According to the principles of scientificity, systematism, operability, dynamism, and comparability, this study selects and optimizes the existing relevant index system according to the connotation of regional innovation capability defined in this paper. Based on this, the order parameter index of regional innovation input and output subsystem is constructed, and the evaluation index of regional innovation capability is constructed systematically, to collect the statistical data of regional innovation development. To ensure the reliability of the data, this study uses the

Figure 1. Method low



statistical data of Anhui's regional innovation development from 2010 to 2019 as the sample. The data is derived from the published statistical yearbook and statistical bulletin, including "China Science and Technology Statistical Yearbook", "Anhui Statistical Yearbook", and "Anhui high tech industry statistical bulletin".

The indexes of data collection are presented in Table 1.

Data Processing

Data Standardization Method

The purpose of standardizing the original index data is to remove the unit limitation of the original index data and transform the original index data into dimensionless index evaluation value, to facilitate

Table 1. The index construction of regional innovation capability evaluation

Composite System	Subsystem	Order Parameter Index	Sign	References
Regional innovation capability	Innovation input	Number of students in regular institutions of higher learning (10^4 people)	X_1	Buesa et al., 2006; Zhao et al., 2013; Shan, 2017
		Full-time teachers of regular institutions of higher learning (10^4 people)	X_2	Buesa et al., 2006; Zhao et al., 2013
		Number of institutions of higher learning (units)	X_3	Autio,1998; Buesa et al., 2006; Chen & Wang, 2012; Zhao et al., 2013; Heindl & Liefner, 2019
		Full-time equivalent of R&D personnel (person-years)	X_4	Prevezer et al., 2013; Zhao et al., 2015; Shan, 2017; Su et al., 2020; Xu et al., 2020
		R&D expenditure (10^9 CNY)	X_5	Zabala-Iturriagagoitia et al., 2007; Zhao et al., 2013; Prevezer et al., 2013; Zhao et al.,2015; Billon et al., 2017; Shan, 2017; Xu et al., 2020
		Expenditures for new product development of industrial enterprises above designated size (10^9 CNY)	X_6	Zhao et al., 2013; Su et al., 2020; Xu et al., 2020
		Number of units with R&D activities (units)	X_7	Asheim & Isaksen, 2002; Chen & Wang, 2012; Shan, 2017; Heindl & Liefner, 2019
		National enterprise technology and engineering center (units)	X_8	Asheim & Isaksen, 2002; Buesa et al., 2006; Chen & Wang, 2012; Heindl & Liefner, 2019
		Mass art galleries and museums (units)	X_9	Polina & Solovyeva, 2019
		Number of employees in culture and related industries (persons)	X_{10}	Zhao et al., 2013; Polina & Solovyeva, 2019
		Number of Internet and mobile phone users (10^4households)	X_{11}	Zhao et al., 2013; Shan, 2017; Ríos-Flores & Ocegueda-Hernández,2017
	Innovation output	Authorized number of three kinds of patent applications (pieces)	Y_1	Buesa et al., 2006; Prevezer et al., 2013; Zhao et al., 2015; Billon et al., 2017; Shan,2017; Su et al., 2020
		Sales revenue of new products of industrial enterprises above designated size (10^4CNY)	Y_2	Zhao et al., 2013; Su et al., 2020; Xu et al., 2020
		Sales revenue of new products of high-tech industry (10^4CNY)	Y_3	Zhao et al., 2013; Su et al., 2020
		Technical market turnover (10^4CNY)	Y_4	Zhao et al., 2013; Su et al., 2020; Xu et al., 2020
		High-tech enterprise output value (10^9CNY)	Y_5	Zhao et al., 2013; Prevezer et al., 2013; Shan, 2017; Ocegueda-Hernández,2017; Su et al., 2020
		Cultural, sports, and media expenditure (10^9 CNY)	Y_6	Buesa et al., 2006; Prevezer et al., 2013; Zhao et al., 2015; Shan, 2017; Billon et al.,2017; Su et al., 2020
		Total postal and telecommunication business (10^4CNY)	Y_7	Zhao et al., 2013; Su et al., 2020; Xu et al., 2020

the comparison and comprehensive evaluation of different indicators. In this study, the min-max method is used to standardize the original index data. Suppose that s_{ij}^{*} represents the standardized value of the jth index in the ith year, s_{ij} represents the original value of the jth index in the ith year, M_j is the maximum value of the *j*th index series, and m_j is the minimum value of the jth index series.The specific calculation steps are as follows:

$$s_{ij}^{*} = \frac{s_{ij} - m_j}{M_j - m_j}, M_j = \max_i \left\{ s_{ij} \right\}, m_j = \min_i \left\{ s_{ij} \right\} \tag{1}$$

In the formula, $s_{ij}^{*} \in \left[0,1\right]$, the maximum value is 1 and the minimum value is 0.

Index Weight Determination Method

Common methods to determine the index weight include entropy weight method (Yang & Guo, 2020), analytic hierarchy process (Heindl & Liefner, 2019), and anti-entropy weight method (Wang et al., 2021). Among the three methods, AHP belongs to the subjective weighting method, and the decision-making or evaluation results have strong subjective randomness and poor objectivity. The other two methods belong to objective weighting method. However, due to the high sensitivity of entropy weight method to the index difference, the extreme cases of index weight often occur. Therefore, this study uses the anti-entropy weight method, which is less sensitive to the different degrees of indicators, to weigh the indexes. Its advantages are reflected in the following three aspects. First, this method can avoid the dilemma of index failure in extreme cases. Second, it can use the original data to reduce the interference of subjective factors on the indicators. Third, it can better reflect the differences between different indexes. The specific calculation steps are as follows:

$$p_j = -\sum_{i=1}^{n} h_{ij} * ln\left(1 - h_{ij}\right), h_{ij} = {s_{ij}^{*}} \Big/ {\sum_{i=1}^{n} s_{ij}^{*}} \tag{2}$$

$$W_j = {p_j} \Big/ {\sum_{j=1}^{n} p_j} \tag{3}$$

In the formula, p_j is the anti-entropy value of the jth index; h_{ij} is the proportion of the standardized value s_{ij}^{*} in the total standardized value of the jth series; W_j is the weight of the jth index determined by the anti-entropy method.

Data Modeling

The common evaluation methods of regional innovation capability include AHP (Heindl & Liefner, 2019), factor analysis (Polina & Solovyeva, 2019), PCA (Pinto & Guerreiro, 2010) and DEA (Xu et al., 2020). These evaluation methods and tools can only measure and evaluate the overall regional innovation capability, and their essence is to regard the regional innovation system as a “black box” system. They are unable to describe the innovation differences and interactions between the internal subsystems (Autio, 1998; Kaufmann, 2000) of the regional innovation system. The composite system synergy degree model can meet this demand to effectively reveal the internal relationship and mechanism of subsystems in the regional innovation “black box” system. Therefore, this study uses this model to measure the synergy effect of innovation input subsystem and innovation output subsystem, and thus excavate the important order parameters that affect the regional innovation capability under the subsystem. Based on the existing research results, using the two subsystems as an example, the Data- driven composite system synergy degree model (Liu et al., 2021) is constructed.

Order Degree of Order Parameter Variable

Suppose that U_1 and U_2 are the subsystems in the development process of the composite system, and the composite system they are composed of is $U = \left\{U_1, U_2\right\}$. For subsystem U_1, set the order parameter variables as $e_{ij} = \left(e_{i1}, e_{i2}, e_{i3}, \ldots, e_{in}\right)$, $i \in \left[1,2\right]$, $n > 1$, $\alpha_{ij} \leq e_{ij} \leq \beta_{ij}$, $j \in \left[1, \mathrm{n}\right]$, α_{ij}, β_{ij} is the critical limit of the order parameter variable at the stable node of the system, which is generally expressed by the minimum and maximum value of the subsystem order parameter variable in the research range. If the order parameter has a positive effect on the development of the subsystem, the order degree of the order parameter is calculated as follows:

$$U_i\left(e_{ij}\right) = \left(e_{ij} - \alpha_{ij}\right) / \left(\beta_{ij} - \alpha_{ij}\right),\ j \in \left[1, m\right] \tag{4}$$

If the order parameter variable negatively affects the development of the subsystem, the order degree of the order parameter variable is:

$$U_i\left(e_{ij}\right) = \left(\beta_{ij} - e_{ij}\right) / \left(\beta_{ij} - \alpha_{ij}\right),\ j \in \left[m+1, n\right] \tag{5}$$

In the above two formulas, $U_i\left(e_{ij}\right)$ represents the order degree of the order parameter variable e_{ij} of the ith subsystem. The closer $U_i\left(e_{ij}\right) \in \left[0,1\right]$ is to 1, the greater its contribution to the order degree of the subsystem, and the closer it is to 0, the smaller its contribution to the order degree of the subsystem.

Subsystem Order Degree Model

$$U_i\left(e_i\right) = \sum_{j=1}^{n} W_{ij} U_i\left(e_{ij}\right),\ W_j \geq 0,\ \sum W_j = 1 \tag{6}$$

In the above formula, $U_i\left(e_i\right)$ represents the order degree of subsystem; W_{ij} represents the contribution of the order parameter index j of subsystem i to the order degree of the subsystem, that is, the weight. From the above formula, $0 \leq U_i\left(e_i\right) \leq 1$, the closer the value is to 1, the closer the subsystem U_i is to order, the higher the order degree of the subsystem, and vice versa.

Composite System Synergy Degree Model

The synergy degree can reflect the degree of synergy development among the subsystems in the composite system. This study builds a composite system synergy degree model based on a subsystem order degree model. In the two-system $\left\{U_1, U_2\right\}$ model, $U_1\left(e_1\right)$ and $U_2\left(e_2\right)$ are the order degrees of the two subsystems measured by the subsystem order degree model. The order degree is dynamic as time in the study interval changes. Assuming that the initial time of the development of the subsystem is 0, the order degree of the subsystem at time 0 is $U_i^0\left(e_i\right)$, the order degree of the subsystem at time t is $U_i^t\left(e_i\right)$, and C is defined as the synergy degree of the composite system, and the synergy degree of the composite system in the dynamic change process with time is:

$$C\left(t\right) = \theta\sqrt{\left|U_1^t\left(e_i\right) - U_1^0\left(e_i\right)\right|\left|U_2^t\left(e_i\right) - U_2^0\left(e_i\right)\right|} \tag{7}$$

$$\theta = \begin{cases} 1, U_1^t\left(e_i\right) - U_1^0\left(e_i\right) > 0 and U_2^t\left(e_i\right) - U_2^0\left(e_i\right) > 0 \\ -1, other \end{cases}$$

According to the formula (7), $C\left(t\right)$ [-1,1], positive and negative effects depend on whether the order degree of its constituent subsystems at time t is greater than that at the initial time 0. The value depends on the order degree of the subsystem at time t, which is equal to the increase of the order degree of the subsystem at time 0. The larger the composite system synergy degree $C\left(t\right)$ is, the higher the synergy degree between the subsystems, and vice versa.

Regional Innovation System is complex in nature and has the characteristics of a complex adaptive system and involves several subsystems (Autio, 1998; Kaufmann, 2000). There are complex non-linear interactions among the subsystems, so the regional innovation system's innovation capability and performance should be further improved through a synergetic effect. According to the complex adaptive system (CAS), once the synergy between the subsystems is lost, the emergence will not exist (Freeburg, 2020). This paper focuses on maximizing the synergetic effect of regional innovation system values, so as to ultimately achieve the goal of improving regional innovation capability. Therefore, this paper intends to analyze and evaluate the regional innovation capability from the perspective of synergy, and the composite system synergy degree model just meets the needs of research methods. This study selects the data of Anhui's innovation capability from 2010 to 2019 as the sample, measures the regional innovation order degree and the overall regional innovation synergy degree from the order parameter index of the two subsystems, and conducts difference and causal analyses on the results. To improve the practical application value of the research results, this study proposes feasible countermeasures and suggestions based on the actual situation of Anhui Province.

Data Application

The research is based on the evaluation and optimization of data-driven regional innovation capability. The specific data application is as follows:

The first step is to construct the evaluation index system of regional innovation capability. By combing the existing research results and considering the two subsystems of innovation input and output, a scientific and reasonable evaluation index system of regional innovation capability is constructed.

The second step is to determine the index weight. Min-max method is used to standardize the original data. On this basis, the anti-entropy weight method is used to determine the weight of each index in the subsystem, which can objectively reflect the importance of each index in the subsystem to the subsystem. At the same time, the determination of index weight prepares for the quantitative evaluation of regional innovation capability.

The third step is the evaluation of regional innovation capability. The order degree of the order parameter variable, subsystem order degree, and composite system synergy degree are measured by using the composite system synergy degree model. According to the measurement results, the vertical comparison and evaluation are carried out to clarify the development trend and law of regional innovation capability, and analyze the problems and obstacles existing in the synergy development of the two subsystems so as to locate the promotional direction of regional innovation capability.

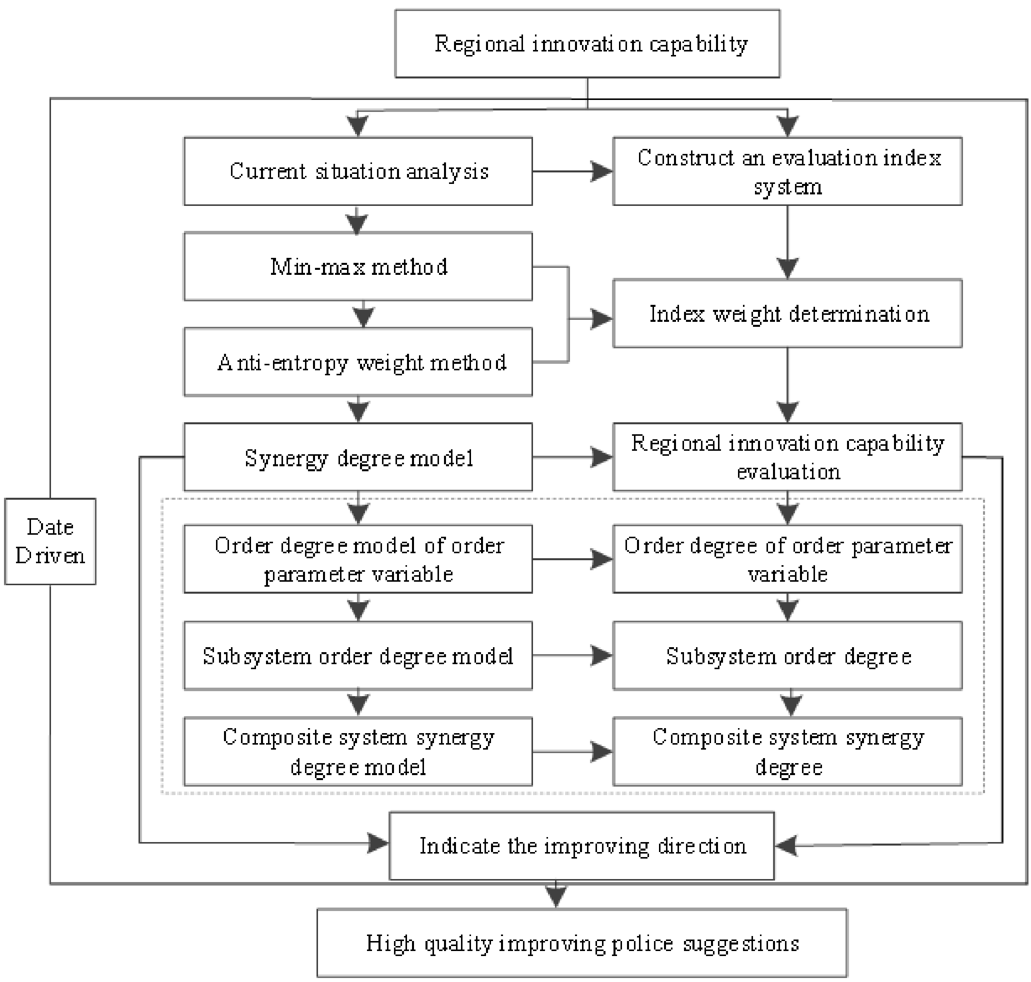
The fourth step is to put forward the countermeasures to improve the regional innovation capability (figure 2). Combined with the development of Anhui regional innovation capability, the step is to find the breakthrough to improve regional innovation capability, and put forward corresponding policy suggestions that will help regional innovation subjects give full play to their respective advantages, form innovation forces, accelerate the transformation of industrial structure, and promote regional synergy development.

CASE STUDY

Background of Anhui Province

Anhui is an inland province in East China. Its GDP in 2019 ranked 11th in the country's 31 provinces and cities. Its regional innovation capability ranked first square array in the country for nine consecutive years. In recent years, with the growth of economic development, Anhui Province has entered the stage of promoting sustainable economic development through innovation, and the construction of innovative provinces has significantly progressed: the proportion of local financial science and

Figure 2. Date application chart of regional innovation capability



technology appropriation in local financial expenditure has increased from 2.8% at the end of the 12th Five Year Plan to 5.1% in 2019; the total number of effective invention patents in the province was 74,812, increasing 1.8 times; there were more than 200 national R & D platforms, an increase of 39% compared with the end of the 12th Five Year Plan; the turnover of technology contracts exceeded 45 billion, an increase of 137.6%. It further highlights the leading role of science and technology in building a new development pattern and promoting high-quality development. Under the background of Anhui's accelerating integration into the Yangtze River Delta, undertaking the high-quality industrial transfer in the Yangtze River Delta, and implementing the innovation-driven development strategy, Anhui's economy is in the key stage of economic transformation and development, and it is important to cultivate new driving forces for economic growth through scientific and technological innovation, to realize the sustainable development of the regional economy. This study examines the regional innovation capability of Anhui Province as the foothold, through the measurement, evaluation, and analysis of the regional innovation capability of Anhui Province, to understand its shortcomings, and to make suggestions for the realization of economic transformation and the promotion of high-quality economic development of Anhui Province.

Results

Given the different units of measurement of the original data of order parameter indexes, it is necessary to standardize the original data of order parameter indexes (table 2 & 3). In the selection of standardization methods, this study uses the max-min method to substitute the original data of order parameter indexes into the max-min method formula (1) for standardization, to realize dimensionless and ensure the accuracy of empirical results.

In this study, the anti-entropy method is used to determine the weight of each order parameter index. The order parameter index data is substituted into the anti-entropy method formula (2) and (3) to obtain the weight of each order parameter index. The results are as follows in table 4.

By substituting the standardized index value into the model formula (4), the order degree of the order parameter index is obtained. By substituting the order degree of order parameter index and the weight of order parameter index into the model formula (6), the order degree of regional innovation input and regional innovation output subsystem is calculated, respectively. Furthermore, 2010 is selected as the base period, the order degree of each subsystem is substituted into the model formula (7), and the synergy degree of the composite system is calculated. The results are presented in Table 5 and Figure 3.

According to Table 5 and Figure 3, the results present that: (1) The order degree of innovation input subsystem in Anhui Province increases from 0.002861 in 2010 to 0.991080 in 2019, and there is no decline in this period, thereby indicating that the innovation input in Anhui Province has achieved high-speed development in an orderly state. (2) The innovation output of Anhui Province had stable growth in 2010-2017, and an accelerated growth in 2018-2019. In 2017, the order degree of innovation output subsystem was 0.564290, and in 2018, it was 0.791326, which was more than 40% higher than that in 2017; in 2019, the order degree of innovation output subsystem reached 0.999402, which indicates that the index synergy degree of innovation output subsystem is high. (3) The synergy degree of the composite system in 2011-2019 is between 0.123787 and 0.993794, which is positive and increases from small to large. From 2010 to 2017, the synergy degree of composite systems recorded a steady growth trend and from 2018 to 2019, the synergy degree of composite systems recorded a rapid growth trend. It can be seen that from 2018 Anhui regional innovation has reached a very significant period of transition and strategic opportunities, and the future innovation capability, innovation vitality, and innovation-driven force have great potential for upgrading.

Discussion

According to the empirical results of the above data, this study analyzes and evaluates the regional innovation capability of Anhui Province from three aspects: the order degree of regional innovation

Table 2. Raw data of order parameter index

Years	Innovation Input											Innovation Output						
	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10	X11	Y1	Y2	Y3	Y4	Y5	Y6	Y7
2010	93.90	4.93	100	64169	163.72	166.77	1484	6	240	84127	3140.72	16012	19971178	841827	461470	4665.00	51.68	3003244
2011	99.13	5.12	104	81087	214.64	236.35	1745	8	251	87718	3716.77	32681	27792518	2586786	650337	6163.70	62.35	3616143
2012	102.30	5.31	107	103045	281.8	279.3	2393	20	262	84644	4116.85	43321	37318538	3898078	861592	6770.70	71.43	4051792
2013	105.21	5.49	106	119340	352.08	324.47	2838	23	274	93121	4601.51	48849	43790809	4199537	1307716	6966.00	79.50	5133986
2014	108.05	5.65	107	129308	393.61	368.52	3433	24	284	81906	4941.38	48380	52808808	5423312	1698343	7161.20	82.25	5860055
2015	113.07	5.81	108	133557	431.75	380.44	3748	30	293	100413	5120.55	59039	58822307	8707151	1905334	7705.10	88.19	7400263
2016	114.50	5.95	109	135830	475.13	443.21	5360	34	292	108668	5418.02	60983	73210508	11080797	2173748	8407.24	84.23	11527847
2017	114.74	6.04	109	140452	564.92	511.71	5298	39	319	112800	6208.00	58213	88430765	14248099	2495697	9221.00	80.94	9153406
2018	113.91	6.11	110	147149	648.95	571.13	5079	39	323	150098	7198.19	79747	95323850	17961823	3213131	10947.00	79.77	25745591
2019	124.12	6.24	112	175318	754.03	619.26	6746	44	342	143173	7708.89	82524	96985530	19031542	4527213	11691.80	87.98	44471270

Table 3. Normalized value of order parameter index

Years	Innovation Input											Innovation Output						
	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10	X11	Y1	Y2	Y3	Y4	Y5	Y6	Y7
2010	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0326	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
2011	0.1731	0.1450	0.3333	0.1522	0.0863	0.1538	0.0496	0.0526	0.1078	0.0852	0.1261	0.2506	0.1016	0.0959	0.0465	0.2133	0.2922	0.0148
2012	0.2780	0.2901	0.5833	0.3498	0.2000	0.2487	0.1727	0.3684	0.2157	0.0402	0.2137	0.4106	0.2252	0.1680	0.0984	0.2997	0.5409	0.0253
2013	0.3743	0.4275	0.5000	0.4964	0.3191	0.3485	0.2573	0.4474	0.3333	0.1645	0.3198	0.4937	0.3093	0.1846	0.2081	0.3275	0.7620	0.0514
2014	0.4682	0.5496	0.5833	0.5861	0.3894	0.4459	0.3704	0.4737	0.4314	0.0000	0.3942	0.4866	0.4264	0.2519	0.3042	0.3552	0.9942	0.0689
2015	0.6343	0.6718	0.6667	0.6243	0.4540	0.4722	0.4303	0.6316	0.5196	0.2714	0.4334	0.6469	0.5045	0.4324	0.3551	0.4326	1.0000	0.1060
2016	0.6817	0.7786	0.7500	0.6447	0.5275	0.6109	0.7366	0.7368	0.5098	0.3925	0.4985	0.6761	0.6913	0.5629	0.4211	0.5326	0.8915	0.2056
2017	0.6896	0.8473	0.7500	0.6863	0.6796	0.7623	0.7248	0.8684	0.7745	0.4530	0.6714	0.6345	0.8889	0.7370	0.5003	0.6484	0.8014	0.1483
2018	0.6621	0.9008	0.8333	0.7466	0.8220	0.8936	0.6832	0.8684	0.8137	1.0000	0.8882	0.9582	0.9784	0.9412	0.6768	0.8940	0.7694	0.5484
2019	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.8984	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.9942	1.0000

Table 4. The weight of order parameter index

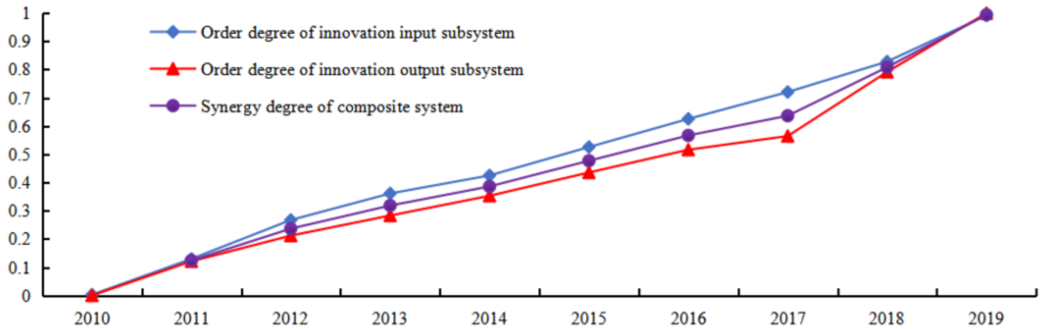
Composite System	Subsystem	Order Parameter Index	Weight
Regional innovation capability	Innovation input	Number of students in regular institutions of higher learning (10^4 people)	0.0838
		Full-time teachers of regular institutions of higher learning (10^4 people)	0.0837
		Number of institutions of higher learning (units)	0.0833
		Full-time equivalent of R&D personnel (person-years)	0.0891
		R&D expenditure (10^9 CNY)	0.0995
		Expenditures for new product development of industrial enterprises above designated size (10^9 CNY)	0.0950
		Number of units with R&D activities (units)	0.1009
		National enterprise technology and engineering center (units)	0.1027
		Mass art galleries and museums (units)	0.0843
		Number of employees in culture and related industries (persons)	0.0878
		Number of Internet and mobile phone users (10^4households)	0.0899
	Innovation output	Authorized number of three kinds of patent applications (pieces)	0.1162
		Sales revenue of new products of industrial enterprises above designated size (10^4CNY)	0.1244
		Sales revenue of new products of high-tech industry (10^4CNY)	0.1587
		Technical market turnover (10^4CNY)	0.1460
		High-tech enterprise output value (10^9CNY)	0.1092
		Cultural, sports, and media expenditure (10^9 CNY)	0.1040
		Total postal and telecommunication business (10^4CNY)	0.2415

Table 5. The order degree of regional innovation subsystems and the synergy degree of composite systems

Years	Order Degree of Innovation Input Subsystem	Order Degree of Innovation Output Subsystem	Synergy Degree of Composite System
2010	0.002861	0.000000	-
2011	0.129477	0.121020	0.123787
2012	0.267024	0.211863	0.236572
2013	0.361056	0.282959	0.318362
2014	0.424952	0.352831	0.385910
2015	0.525430	0.435271	0.476927
2016	0.624987	0.515914	0.566537
2017	0.720129	0.564290	0.636197
2018	0.827881	0.791326	0.807997
2019	0.991080	0.999402	0.993794

input subsystem, the order degree of regional innovation output subsystem, and the synergy degree of regional innovation composite system.

Figure 3. The order degree of regional innovation subsystems and the synergy degree of composite systems



The Order Degree of Innovation Input Subsystem Is Increasing Yearly

Increasing input in innovation is an important prerequisite for innovation-driven development and an inevitable requirement for the high-quality development of a regional economy. In the past, specifically between 2010 and 2019, the order degree of Anhui innovation input subsystem has increased yearly, which is consistent with the rapid growth of the total innovation investment and the increase of investment intensity year-by-year that is reflected in the original data. This situation is because Anhui Province is focusing on the construction of innovative provinces and continuously stimulating the innovation vitality of the whole society. A series of scientific, reasonable, active, and effective innovation-driven development strategies and policy measures have been introduced and implemented. On the one hand, vigorous input into colleges and universities construction, combined with the original data, showed that by the end of 2019, there were 112 colleges and universities in Anhui, with 1,241,200 students and 62,400 full-time teachers. On the other hand, by increasing input in science and technology, the proportion of scientific research input in Anhui is constantly increasing. In 2019, the internal R&D expenditure was 75.403billion yuan, accounting for 2% of the GDP; the full-time equivalent of R&D personnel reached 175,318 person-years, an increase of 19.1% over the previous year.

The Order Degree of Innovation Output Subsystem Is Increasing Yearly

This benefited Anhui's in-depth implementation of the innovation-driven development strategy and accelerated the transformation of scientific and technological achievements into actual productivity, which led to regional innovation output benefits and fruitful innovation results. Combined with the original data of innovation output order parameter index, in 2018, the three different patent applications granted in the province reached 82,524, an increase of 37% over 2017. Among them, the patents of companies and enterprises have grown rapidly and had strong momentum. The sales revenue of new products of high-tech industries accounted for 18.8% of the sales revenue of new products of industrial enterprises above designated size. The output value of high-tech enterprises exceeded one trillion yuan for the first time, and the turnover of the technology market reached 32.131 billion yuan. In 2019, the three different patent applications granted in the province reached 82,524, a yearly increase of 3.5%, and the invention patent grant rate reached 23.78%; the turnover of technology market reached 45.272 billion yuan, a yearly increase of more than 40%, reaching a record high.

The Synergy Degree of Composite System Is Increasing Yearly

The synergy degree of composite system is increasing yearly, indicating that the interaction between the two subsystems of Anhui innovation output and innovation input is being gradually strengthened, and the synergy development mechanism is gradually being formed, which promotes the continuous improvement of regional innovation capability and which is consistent with the regional innovation capability of Anhui Province shown in the evaluation report of China's regional innovation capability in 2010-2019. It is also in line with the current situation of economic development in Anhui. In 2018, Secretary Xi Jinping announced that the integration of the Yangtze River Delta had become a national strategy, that the regional innovation capability of Anhui had been rapidly upgraded. Furthermore, according to Figure 3, although the regional synergy innovation capability of Anhui Province has been continuously enhanced from 2010-2019, the innovation output and innovation input have not achieved synchronous development, and the regional innovation output capability still lags behind the regional innovation input capability to a certain extent. In the future, the regional innovation synergy degree and regional synergy innovation capability of Anhui Province still have room and potential for further improvement. Additionally, although the number of patents created and owned in Anhui Province has maintained a rapid growth trend, its improvement should be reflected in the quality of industrial development. Transforming the advantage of patent quantity into the core competitiveness to promote the high-quality development of the industry is a problem that the government and enterprises should face together.

Policy Suggestion

This study evaluates and analyzes the regional innovation capability of Anhui Province based on the data-driven composite system synergy model, and accurately diagnoses the current situation and existing problems of the regional innovation capability of Anhui Province. Since 2010, Anhui has seriously implemented the innovation-driven development strategy, accurately implemented various tasks, strengthened regional innovation, and continuously optimized synergy development. Anhui's regional innovation capability has been continuously improved. This study proposes the following policy suggestions to improve the regional innovation capability of Anhui Province.

Effective Allocation of Regional Innovation Resources

There are many problems in regional innovation resources in China, such as repeated construction, low utilization efficiency, unreasonable resource allocation, scattered innovation investment, and so on. Given the current situation of regional innovation resources and the limited government investment (Liu et al., 2021), we should improve the integration mechanism of regional innovation resources, strengthen the optimal allocation of regional innovation resources, and realize the co-construction, co-sharing, and co-exploitation of innovation resources.

First, based on the Yangtze River Delta region, as an important member of the Yangtze River Delta "big family", Anhui should strive to improve the level of co-construction, co-sharing, and co-exploitation of high-quality innovation resources between Anhui and the central area of the Yangtze River Delta, and promote the seamless docking of collaborative innovation development and cooperation among the three provinces and one city in the Yangtze River Delta integration. The whole city should actively participate in the division of labor and cooperation in the Yangtze River Delta, actively undertake industrial transfer, and comprehensively dock with the central area of the Yangtze River Delta, to promote the Anhui region to integrate into higher quality and integrated development of the Yangtze River Delta. Second, based on the Anhui region, we should strengthen the concentration of innovation elements in Hefei, conduct overall planning together with the other eight cities, actively explore the integration mode and operability of different innovation resources among cities in the region, break the barriers of resource fragmentation and department closure among cities, and strengthen multi-dimensional cooperation in more fields and channels among cities in the region. We should promote the synergy development of the whole province and promote the free diffusion, rational allocation, open sharing, and efficient utilization of regional innovation resources. Furthermore, it is necessary to focus on technological innovation, system and mechanism innovation, promote the aggregation effect of science and technology, industry, capital, and talent policies, enhance the level of co-construction, co-sharing, and co-exploitation of innovation resources, create new kinetic energy for synergy development of regional innovation, and enhance the overall regional innovation capability and competitiveness of Anhui.

Construction of Industry-Academia-Research Synergy Innovation

Industry-academia-research synergy innovation has incomparable advantages, which can increase the benefits of synergy cooperation (Hohberger et al., 2015). It is necessary to actively build a regional industry-academia-research synergy innovation mechanism with enterprises as the main body, market as the guidance, and colleges and research institutes as the technical support, to cultivate, guide, and support various innovative elements to gather with industries and enterprises in Anhui.

First, we should strengthen the dominant position of enterprise innovation. On the one hand, it is necessary to actively implement the cultivation plan of innovative enterprises, and vigorously cultivate and develop several high-tech enterprises with independent intellectual property rights, core technology, strong international competitiveness, and radiation ability. On the other hand, leading enterprises of science and technology in the region should be guided to establish a strategic alliance of industrial technology innovation with small and medium-sized enterprises, universities, and scientific research institutes, and actively seek to establish an interconnected innovation mechanism of knowledge sharing, resource sharing, and talent sharing. We should actively promote the agglomeration of innovation elements to enterprises, and transform innovation output into economic benefits, to promote the high-quality development of the regional economy. Finally, we should encourage powerful high-tech enterprises to build high-level R & D institutions, implement patent layouts, realize the transformation of intellectual property creation from "focusing on quantity" to "focusing on quality," realize the transformation of intellectual property application from "focusing on ownership" to "focusing on application," and build the whole chain operation mode of R & D, production, and sales.

Soundness of Regional Innovation Policy Guarantee

To promote the coordinated development of regional innovation in Anhui, we should evaluate the requirements of the new development theory, accelerate the implementation of regional innovation development strategy, improve the regional innovation policy, and constantly deepen and improve from the policy guarantee level. The soundness of regional innovation policy guarantee mechanism can effectively play the guiding role of innovation policy, and thus enhance the collaborative efficiency of innovation input and output.

Firstly, the patent navigation decision-making mechanism of emerging industries should be improved. We should implement the strategic action plan of intellectual property, create a good legal environment for intellectual property, and advance the management and service of intellectual property. With the help of big data analysis, we can accurately grasp the inherent law and influence the degree of patents in industrial development, scientifically refine the direction of technological innovation, actively guide and encourage enterprises, universities, and scientific research institutes to implement intellectual property layout around emerging industries. Secondly, the financial support mechanism should be improved. On the one hand, we should continue to raise the proportion of basic and applied basic research funds in R & D funds. On the other hand, in addition to the central finance, other social forces should be encouraged to participate in basic research and jointly promote the development of basic scientific research. Furthermore, it is necessary to provide more accurate and efficient financial support for scientific and technological achievements, industrialization projects, and scientific and technological innovation enterprises with capital demand. Finally, the mechanism of talent introduction should be innovated. On the one hand, the government should introduce "three high" scientific and technological innovation talents with high education background, high work experience, and high-tech experience, and strengthen the tracking service for the introduction of scientific and technological innovation talents. On the other hand, patent agents and technology brokers play a "lead through" role in the co-construction, co-sharing, and co-exploitation of regional innovation resources. The government should introduce patent agents and technology brokers, to improve their comprehensive quality and professional level.

Managerial Implication

Through the comparative analysis with the existing literature (Shan, 2017; Su et al., 2020; Xu et al., 2020), this study has the following advantages. First, this study constructs the evaluation index of regional innovation capability from the perspective of the input-output subsystem based on analyzing and refining the influencing factors of innovation-driven mode, to collect regional innovation data and provide scientific, objective, and effective measurement standards for the quantitative research of regional innovation capability under data-driven evaluation method. Second, the composite system synergy degree model is used to realize the dynamic evaluation of regional innovation capability from the perspective of synergy, reveal the changing trend and relationship between regional innovation subsystem and composite system innovation capability, analyze the reasons and existing problems, and provide some guidance for the promotion path of regional innovation capability. Third, the study formulates reasonable optimization mechanism and policy suggestions based on deepening the internal index structure of regional innovation capability, which provides strong support for the government to coordinate multi-party innovation forces, optimize the allocation of innovation resources, and do a good job in the top-level design.

Combined with the above research and conclusions, we get the following management implications.

First, different regions have different resource endowments and technological bases, and the key points and implementation strategies of regional innovation capability should be different. It is necessary to design a set of scientific and reasonable evaluation index systems of regional innovation capability according to the characteristics of the region. Moreover, the objective evaluation of the specific regional innovation capability can help the regional government to understand and grasp the development status of the regional innovation capability, clarify the characteristics and existing problems of the main influencing factors of the regional innovation capability, and provide a reasonable direction for the region to take measures to improve its regional innovation capability.

Second, in the overall framework of the national innovation system, the regional innovation composite system plays an important role. The regional innovation composite system is a complex ecosystem with multiple innovation inputs and outputs, involving many indicators, which interact and change dynamically. The collaborative relationship between innovation input and innovation output affects the level of regional innovation capability. Therefore, the identification and analysis of various influencing factors of regional innovation composite systems are conducive to improving the operation performance and innovation ability of the regional innovation composite system.

Third, regarding big data, data are driving the transformation of the regional innovation governance model (Sultana et al., 2021). Using data accurately and conveniently has become an important exploration direction of "regional innovation governance" and "data resource" utilization of governments in various countries. We should adopt the information advantages of big data, realize the automatic extraction and integration of regional innovation index data, and with the help of data-driven evaluation methods, more comprehensively and finely explain the development status and change trend of regional innovation capability, to provide powerful data and intellectual support for the evaluation of regional innovation capability.

CONCLUSION

With the increasingly serious environmental pollution and the deteriorating resource crisis in the world, human beings are facing a major challenge of realizing the sustainable development of the economy and resources .Practicing the regional innovation-driven development model under the dual constraints of limited resources and environmental protection is an urgent requirement to overcome the challenges of peak carbon emissions and carbon neutrality, and to achieve high-quality and sustainable development of the global economy. Therefore, innovation capability has become the key to enhancing regional competitiveness and promoting the quality of economic development. It is urgent to effectively evaluate and optimize regional innovation capability under the innovation-driven development mode, to promote regional economic transformation, upgrade, and promote sustainable and high-quality development of a regional economy.

This study proposes a data-driven method to measure, evaluate, and optimize regional innovation capability. The main innovation points are as follows: (1) building evaluation indexes of regional innovation capability. This study constructs scientific and reasonable evaluation indexes of regional innovation capability from the perspective of the input-output subsystem. (2) The evaluation model of regional innovation capability based on synergy perspective is constructed. Through the composite system synergy degree model, this study objectively and effectively evaluates and analyzes the regional innovation capability of Anhui Province from a synergy perspective, reveals the characteristics of regional innovation capability and the problems existing in innovation-driven development, and provides a quantitative reference for subsequent policy formulation and adjustment. (3) Based on Anhui's regional resource endowments and strategic opportunities, this study uses innovation-driven development as a breakthrough point, firmly grasps the focus of regional innovation capability improvement, formulates targeted policy recommendations to promote the improvement of Anhui regional innovation capability, and helps government departments to guide and standardize regional innovation-driven development trajectory.

The improvement of regional innovation capacity plays an important role in realizing the high-quality development of the regional economy and the optimization of the industrial structure. This research is of great significance because it accelerates the improvement of regional innovation capability, promotes regional innovation-driven development, and accelerates the pace of high-quality regional development. However, the research on regional innovation capability evaluation is a wide-ranged complex system engineering. Given the complexity of the regional innovation composite system and the availability of data, the integrity of the regional innovation capability evaluation index system should be further explored. Furthermore, in future research, we can increase the dynamic comparison and analysis of regional innovation capacity with different provinces, which is more conducive to comprehensively and precisely reveal the current situation and changing trend of regional economic innovation development, decipher the shortcomings and deficiencies that affect the regional economic innovation development and propose more effective suggestions for the high-quality development of a regional economy.

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