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Research Article

An Empirical Study Evaluating the Symbiotic Efficiency of China's Provinces and the Innovation Ecosystem in the High-Tech Industry

Jianzhao Yang [1,2]

[1]School of Economics and Management, Harbin Engineering University, Harbin, Heilongjiang, China
[2]Yiwu Industrial & Commercial College, Yiwu, Zhejiang, China

Correspondence should be addressed to Jianzhao Yang; yangjz@ywicc.edu.cn

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The traditional innovation model has been unable to adapt to high-speed development, so the role of the innovation ecosystem has become more important. In this paper, we introduce ecology into industrial innovation and construct the symbiotic model to study the symbiotic evolution process of the high-tech industrial innovation ecosystem. This paper takes China's national high-tech industrial park as a case to study its symbiotic efficiency through empirical research, which uses a stochastic frontier analysis as a research method, constructs a complete index evaluation system, and analyzes the influencing factors. According to the results, we find that an environment conducive to the symbiotic efficiency has emerged, but development and efficiency of high-tech ecosystems in different regions of China are highly dispersed and unbalanced. There is room for improvement in symbiosis efficiency, but the difficulty is gradually increasing. Based on the evaluation of symbiotic efficiency of innovation ecosystem of high-tech industry and the consideration of influencing factors such as policy, economy, society, and technology, this paper puts forward the countermeasures of high-tech industry supporting regional economy.

1. Introduction

The acceleration of economic globalization and the increase in and development of the knowledge economy have had profound impacts on production modes, economic growth modes, and industrial development structures [1]. The high-tech industry—represented by information, new material, and space technologies—shows good development prospects. The high-tech industry shows the characteristics of high knowledge intensity, high innovation, and low pollution, which not only symbolize national or regional economic competitiveness and scientific and technological strength but also act as the driving force of national economic development and the direct embodiment of today's national and regional competitiveness.

As the international environment becomes more complex, the international innovation strategy has also produced new changes. When their own innovation resources and abilities cannot meet their innovation requirements, an increasing number of high-tech enterprises realize that they must strengthen their cooperation and communication with the internal and external innovation subjects of the industry to create a new mode of cooperative innovation. The change in the innovation paradigm has attracted much attention [2]. There are an increasing number of studies on open innovation [3], innovation networks [4], and collaboration among innovation subjects [5]. The concept of an innovation system is proposed to realize the progress of the innovation paradigm from linearity to systematization [6], and the concept of an innovation ecosystem is gaining scholarly respect.

"Ecosystem" was proposed by A. G. Tansley in 1935 and mainly refers to a certain spatiotemporal range from the system perspective to maintain the effect of natural biological and environmental associations through natural force regulation. Later, the ecosystem concept extended from natural science to economic management and sociology and was then applied to human ecology, business ecosystems, and a series of research results mainly used to study the laws and mechanisms of the interactions between life and environmental systems. As a system structure based on ecological metaphors, the innovation ecosystem follows the principles of organizational evolution. Various enterprises within the high-tech industry occupy appropriate nodes in the innovation network through the separation of the ecological niche [7], which obtains the resources needed for innovation and development, enhances their internal innovation ability, and gradually evolves into a modular coexistence and evolution of the high-tech industry innovation ecosystem with knowledge and technology as the core competitive resources [8]. The symbiosis of the high-tech industry innovation ecosystem is carried out around the core enterprises. As the various subjects cooperate, they began to have the characteristics of "symbiosis," similar to ecology [9]. When innovation activities begin, each innovation subject forms a relatively stable symbiotic system with core enterprises to reduce innovation costs and improve innovation returns by providing supporting functions and values such as research and development, resources, technology, and services. In the interaction with the innovation symbiotic environment, such as policies and cultures [10], the symbiotic evolution forms an open symbiotic innovation community; realizes the comprehensive integration of innovation technology, products, and services at the system, function, and time levels; and prepares for further innovation evolution and upgradation of the innovation ecosystem [11].

Symbiosis is one of the most widely used theories in the field of ecology. It mainly refers to two organisms that rely on each other, cooperate and depend on each other, compete for favorable positions, and jointly promote the evolution and progress of groups. It has been gradually applied to the field of social science. Symbiosis in economics mainly emphasizes the relationship between industrial development, the ecological environment, and natural resources and is similar to the concepts of sustainable and harmonious development as well as the circular and green economy. In the industrial system, enterprises of different natures form an industrial "food network" through the exchange and utilization of material, energy, or information to improve their own and the economic, environmental, and social benefits of the system. This phenomenon is called industrial symbiosis [12]. Frosch and Gallopoulo defined industrial symbiosis and industrial ecological networks [13]. Ehrenfeld first proposed the concept of industrial ecosystems and pioneered the combination of symbiosis theory and industrial ecology [14]. Fransman first combined an innovation ecosystem with industry to study the components and main influencing factors of ICT (information and communication technology) industry innovation [15]. These research results combine symbiosis with industrial innovation ecosystems from the perspective of economics, laying the research foundation for the application of symbiosis theory in the field of economics. Hu believes that industrial symbiosis is an objective economic phenomenon. The internal and external causes of symbiotic relationships are the continuity and value-adding potential of the industrial chain [16]. Li analyzed the formation of the process of symbiotic relationships in industrial innovation ecosystems [17].

In the innovation ecosystem of high-tech industry, each innovation subject transmits material and energy through symbiosis, and also realizes the circulation of material and energy with the external environment. This symbiosis network structure is an important driving force for the development of high-tech industry. In order to improve the innovation efficiency of the entire industry and improve the support of industrial innovation to economic development, it is necessary to change the traditional concept of emphasizing the input-output efficiency between individuals to emphasizing the synergy and symbiosis efficiency among various innovation entities. Through the scientific evaluation of the symbiosis efficiency of the innovation ecosystem of the high-tech industry, the influencing factors of the symbiosis efficiency are analyzed, the problems existing in the innovation development are found, and improvement strategies are put forward, so as to continuously improve the innovation ability of high-tech industries and the important role in promoting economic development. This paper evaluates the symbiotic efficiency of the innovation ecosystem in the high-tech industry [12]. Such an evaluation is mainly based on the economic connotation of efficiency. The method abstracts the interference factors and calculates the conversion efficiency between the symbiotic inputs and outputs of the high-tech industry innovation ecosystem using the empirical research model that fits mainstream economics as a research tool. For the study of symbiotic efficiency evaluation, it is mainly divided into the construction of index system and method selection. Simatupang designed corresponding evaluation index systems for regional collaborative innovation [18], Fan for technological collaborative innovation [19], and Maleckie for science and technology parks [20]. In terms of research methods, Bhagwat used analytic hierarchy [21] and Philbin established a transformation-based evaluation model [22]. For the relevant research on high-tech industries in China, Liu constructed an evaluation model for the performance of regional collaborative innovation [23], Ye used the DEA method to study the symbiotic efficiency of regional collaborative innovation networks [24], and Duan used the DEA method to evaluate the efficiency of the symbiotic system [25].

Through the combing of the current research status, it can be found that there are certain deficiencies in the current research, which are mainly reflected in three aspects: (1) although the current research has paid attention to the synergistic relationship between different governments, universities, research institutions, and other innovative subjects, there are many innovative subjects in the innovation ecosystem, and there is a lack of macro perspective to conduct overall research. (2) For the phenomenon of symbiosis, the existing research is mainly considered from a linear point of view, ignoring the entire symbiotic formation process. Insufficient research on symbiotic patterns can lead to insufficient representation of complex system properties of ecosystems. (3) Regarding the evaluation of symbiotic efficiency, most scholars use the DEA research method of multi-input and multi-output, and fail to determine the production function, so the integrity of the entire innovation ecosystem is insufficient.

This paper introduces ecology into industrial innovation, studies the symbiotic evolution process of the high-tech industrial innovation ecosystem through the concepts of the ecosystem population, community, and symbiosis, clarifies the symbiotic model of the high-tech industrial innovation ecosystem, and scientifically studies its symbiotic efficiency through empirical research. This paper is arranged as follows:

(1) The paper studies the symbiotic model of the high-tech industry innovation ecosystem. The symbiotic structure is designed based on the symbiotic relationship of the high-tech industry innovation ecosystem. From the perspective of the composition of the innovation ecosystem, the innovation subject constitutes a complex network with its natural, social, and economic environment. From the perspective of a complex network metaphor innovation ecosystem, the innovation subjects in the system are composed of complementary organizations closely coordinated by core enterprises, upstream component suppliers, customers, and downstream complementary suppliers. A complex network provides symbiotic conditions for industrial innovation ecosystems and creates system design conditions and flexible partner selection relationships for innovation subjects. The cost of establishing partnerships between innovative populations and the degree of embedding innovative populations into networks in an innovative ecosystem is complex network formed by the nature of resource interdependence. According to the theory of complex systems, from linearity to reticulation and finally to the three-structure network, system complexity is fully embodied. Combined with the relationship between innovation subjects, the symbiotic model of the innovation ecosystem of the high-tech industry is designed to lay a good foundation for efficiency research.

(2) For the symbiotic efficiency of innovation ecosystems in high-tech industries, the evaluation methods are scientifically selected, the index system is constructed, and its evaluation model is designed.

(3) Based on previous research, this paper takes China's national high-tech park as the empirical object to study the symbiotic efficiency of the high-tech industry innovation ecosystem.

(4) The results are analyzed, and the conclusion is given. The symbiotic mode of the innovation ecosystem of the high-tech industry was that the innovation subject forms the symbiotic system through complex connections according to the symbiotic structure and suitable partners according to the principle of niche separation. We found that the input of symbiotic resources in terms of investment had a positive impact on symbiotic efficiency. The impact of the influencing factors on symbiotic efficiency was not consistent.

2. Innovation Ecosystem Symbiotic Model

2.1. Symbiotic Structure. The innovation ecosystem of the high-tech industry includes innovation subjects—such as enterprises, research institutes, universities, governments, intermediaries, and financial institutes—which are connected through innovation chains. Based on biological symbiosis theory and combined with the research methods of innovation, economics, ecology, and other disciplines, this paper examines and summarizes the operational process of the innovation ecosystem in the high-tech industry. This paper summarizes the three symbiotic structures of the innovation ecosystem: species, populations, and communities. The symbiotic network of the innovation ecosystem evolves along the path of "point (species) ⟶ chain (population) ⟶ surface (population) ⟶ network (community)." The formation of a symbiotic network benefits from the interconnection among symbiotic populations. The interconnection among symbiotic populations comes from the coupling communication of these, and the communication of these populations comes from the inextricable connection among symbiotic species in the final analysis [26].

Symbiotic species are produced in the smallest unit of symbiotic innovation. All kinds of innovative species—such as core, manufacturing, and service enterprises; scientific research institutes; universities; governments; and intermediaries—are the basic units of symbiotic relationships in the innovation ecosystem of the high-tech industry. They have the necessary information, technology, talent, funds, policies, and other resource conditions for systems and innovation.

After innovation opportunities emerge, the innovation linkages between several symbiotic species tend to make innovation symbiotic choices under the influence of the market as well as innovation cost, risk, and benefit [27]. This symbiotic choice does not have the purpose of survival, nor is it simple coexistence, but it permits the integration and development of the innovation chain [28]. Each symbiotic species carries out symbiotic selection according to its own innovation points, seeking niche redistribution through symbiosis. In addition, each innovation subject seeks solidification in the innovation chain to maximize benefits [29]. Once a symbiotic relationship is formed, the abilities of self-organization, evolution, and reinnovation are greatly enhanced, and the ability to resist external adverse factors is strengthened [30]. As the system operates, mutation and evolution abilities are generated, as are the innovation genes that are more suitable for the innovation ecosystem to improve the collaborative innovation and reinnovation abilities of the system. The innovation environment also provides feedback on the relationship between the symbiotic species, and the healthy development of the symbiotic populations includes both the same and different species; the standard of division is the similarity of niches in their innovation chain. Populations with similar niches tend to be similar in resource, technology, and market demands, and their innovation objectives and achievements are similar. The explosive growth of a single-species population may lead to the rapid depletion of some specific resources, the failure of market allocation, the waste of human, material and financial resources, and ecosystem disasters. Therefore, populations of the same species are characterized more by competitive symbiosis. Different species reflect more cooperative symbiotic relationships than do the same species. Different species have different divisions of labor, forming innovation, industrial, and value chains and other intimate cooperations [31], which permit the symbiotic formation and evolution of the high-tech industry innovation ecosystem. The symbiotic system is affected by external measures such as reward and punishment.

Symbiotic communities are also divided into intra- and intercommunities. Communities are collections of populations. Different intra- and intercommunity populations form a network distribution. To realize the innovation enthusiasm of enterprises, universities, scientific research institutes, governments, and other species in the system symbiotic mode, a two-way incentive must be realized of the reasonable interest distribution of each population in innovation achievements, and the smooth operation of the system must be ensured. The innovation ecosystem continues to have an innovation culture and system. These innovation cultures and systems have no specific rules. They are cultural and institutional atmospheres gradually formed under various complex factors and different environmental impacts. Cultures and institutions in the system constitute the system environment community. Environmental communities include tangible and intangible environments, which are not replicable and are difficult to form directly within the system. Biological and environmental communities are interrelated and interact with each other; they embody the competition and symbiosis of innovative ecosystems. The symbiotic system of the innovation ecosystem in high-tech industries is shown in Figure 1.

2.2. Symbiotic System. In the natural ecological system, symbiosis first occurs among different individuals with survival needs, and the initial symbiosis is formed for survival [32]. As symbiosis forms, individuals continue to match and find the best interests for achieving win-win symbiosis. After individual symbiosis is achieved, it should also be tested by the natural environment [33]. The symbiotic innovation community of the high-tech industry innovation ecosystem is mainly composed of innovative enterprises, colleges and universities, scientific research institutions, supporting enterprises, intermediaries, market customers, and other populations [34]. The species of innovation enterprises and other innovation subjects collaborate according to various matching conditions and become the core innovation population. Universities and research institutions form a population that undertakes personnel training and technical support. They couple with core populations to form symbiotic population relationships and provide original innovation while obtaining financial and material support. The innovation core population converts the original innovation results into products and services that are transported to the market application population from service intermediaries and terminal enterprises to the market. The market application population brings direct market impetus to the innovation core population. At the same time, the market application population interacts with the population of innovation enterprises, universities, and research institutions through information feedback and kernel drive and promotes the original innovation to be closer to the market demand to form an effective symbiotic system.

The symbiotic system of a high-tech industrial innovation ecosystem is mainly composed of three stages: the selection of symbiotic partners, the distribution of symbiosis interests, and the governance of the symbiotic system. Finally, it realizes the efficient symbiosis of various elements within the high-tech industrial innovation ecosystem. The three symbiosis stages of realizing the innovation ecosystem of the high-tech industry are the selection of symbiotic partners, the distribution of symbiotic interests, and the governance of the symbiotic system. Regardless of the stage, it is necessary to rely on the specific political, economic, social, and technological environment to realize the symbiotic stability of the high-tech industry innovation ecosystem. The transformative relationship between various resource inputs and symbiotic-level outputs determines the symbiotic efficiency of the high-tech industry innovation ecosystem.

3. Evaluation Method

3.1. Selection Basis. The innovation ecosystem of the high-tech industry strengthens the interaction of innovation subjects, shares and complements resources of different innovation subjects through an innovation ecosystem, and produces symbiotic effects. It has many characteristics similar to biological communities, such as competitiveness, collaboration, and environmental adaptability. In the symbiotic system, the innovation subjects exchange material, information, and energy through symbiotic cooperation to obtain innovation output. The innovation ecosystem of the high-tech industry, which forms a symbiotic system, mainly promotes the stable and orderly operation of symbiotic elements within the system by forming symbiotic interests within it [35]. Thus, the symbiotic level of the main elements of innovation in the innovation ecosystem has become a key factor in determining the symbiotic efficiency of the innovation ecosystem of high-tech industries. This level can be evaluated by the symbiosis degree index, so the symbiotic efficiency evaluation of the high-tech industry innovation ecosystem is an efficiency evaluation process of unit output.

The innovation ecosystem of the high-tech industry pursues the best symbiotic level. Therefore, when evaluating the symbiotic efficiency of each evaluation unit, we focus on the

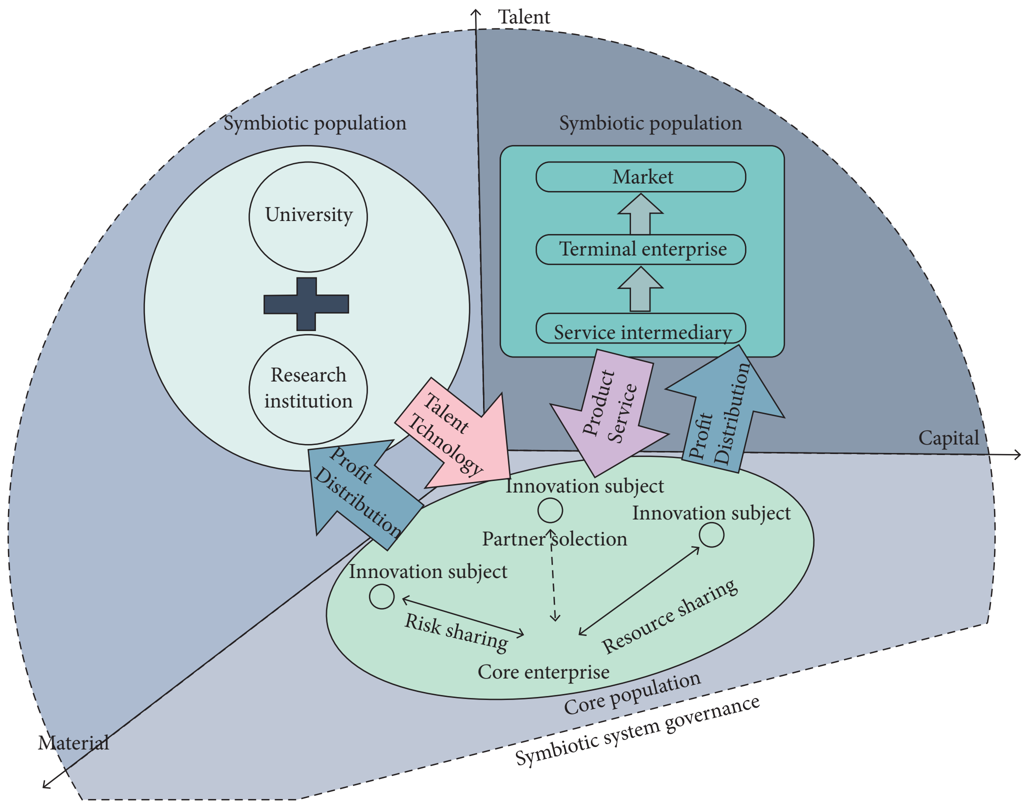

Figure 1: Symbiotic system of innovation ecosystem in high-tech industry.

"distance" from the efficiency frontier. This process first considers the symbiotic input and output factors on efficiency. The symbiotic efficiency of the high-tech industry innovation ecosystem is not directly related to the innovation output of each evaluation unit. Therefore, the process is relatively less affected by various explicit performance indicators and is greatly affected by a random factor. The SFA can fully consider the characteristics of the impact of random factors. In addition, it can include the connotation and characteristics of the symbiotic efficiency of the innovation ecosystem of the high-tech industry. This paper uses the SFA to evaluate the symbiotic efficiency of the innovation ecosystem of the high-tech industry and realize the one-step measurement of these factors.

3.2. Method Introduction. SFA method is an estimation method used for estimating the technical efficiency which was proposed by Aigner and Meeusen almost simultaneously and independently [36]. The SFA method uses the production function to construct the frontier and uses the conditional expectation of the technical inefficiency term as the technical efficiency value. Therefore, the evaluation results measured by SFA method are not easy to be affected by special evaluation units, and there will be no case that the efficiency value of evaluation unit is same with others. In addition, when the sample number of evaluation units is large, the evaluation results of SFA method are more reliable and comparable than that of DEA model [37]. In the process of evaluating the efficiency of the evaluation units, SFA method assumes that the production frontier of each evaluation unit is random, and divides the error term of production function into random error and technical invalid error. After the progress from analyzing cross-sectional data to processing panel data, SFA method introduces the explanatory variable of technical efficiency, so the parameter estimation of production function and technical efficiency regression equation is obtained through one-time regression.

As a representative of the parameter method, the SFA can effectively measure the efficiency of the unit output by establishing functional relationships [38]. The SFA allows for statistical noise in the efficiency measurement, can effectively distinguish different efficiency evaluation units, and can control the heterogeneity of the model. The SFA is based on the average reference value of the regression model. Therefore, when a single data point or a small number of data points fluctuate, the model still has strong stability. Therefore, using the SFA as an evaluation method, the symbiotic efficiency of the innovation ecosystem of high-tech industries not only has high applicability but also has more prominent reliability [39].

3.3. Index System. The combination of innovation ecosystems in the high-tech industry focuses on the interdependence and harmonious coexistence of various elements of innovation ecosystems [23]. Therefore, the symbiotic efficiency of the innovation ecosystem of the high-tech industry mainly focuses on the transformative relationship between the input and co-production of various elements of the innovation ecosystem in the process of forming a symbiotic system. Therefore, this paper sets the output index of the symbiosis efficiency evaluation of the high-tech industry innovation ecosystem as the symbiotic degree of the innovation ecosystem. In addition, the input index is the resource input of the internal symbiotic system of various groups of innovation ecosystems.

3.3.1. Evaluation Index of the Output Factors. Based on the idea of synergy and the research results of Li and other scholars [40], this paper evaluated the output of the symbiotic system of the high-tech industry innovation ecosystem with the symbiotic degree as the output index [41]. The symbiotic degree, as an index for measuring the relationship and synergy level of symbiosis within and between populations in the innovation ecosystem of high-tech industry, is affected by the quantity, quality, and interaction of various population elements in the innovation ecosystem. Therefore, the evaluation of the symbiotic degree needs to consider multiple symbiotic elements, such as the unit, matrix, platform, network, and environment. Hence, this paper measured the symbiosis degree of the high-tech industry innovation ecosystem through the following process.

First, the order parameter of the symbiotic population was determined as

$$X = \left\{x_{ij}, (i = 1, 2, \ldots, 5; j = 1, 2, \ldots, n)\right\}. \quad (1)$$

In the formula, x_{ij} represents the j-order parameter representing the symbiotic level of symbiotic population i, and $\beta_{ij} \leq x_{ij} \leq \alpha_{ij}$. For the positive influencing factors, the order parameter's order degree of the symbiotic population is

$$\mathrm{d}_{ij}\left(x_{ij}\right) = \frac{x_{ij} - \beta_{ij}}{\alpha_{ij} - \beta_{ij}}. \quad (2)$$

Second, the order parameter's order degree of the symbiotic population was integrated by the geometric weighting method, and the symbiotic level of the symbiotic population in the high-tech industry innovation ecosystem could be obtained. The formula is

$$\mathrm{dsm}_i\left(x_i\right) = \prod_{j=1}^{k} \mathrm{d}_{ij}\left(x_{ij}\right)^{\lambda_{ij}}, \lambda_{ij} \geq 0, \sum_{j=0}^{n} \lambda_{ij} = 1. \quad (3)$$

In this formula, $\mathrm{dsm}_i(x_i)$ represents the symbiotic level of symbiotic population i, and λ_{ij} is the weight. The weight was determined by the correlation coefficient method. The following are the steps:

Assuming that the index system has n indicators, the correlation coefficient matrix is as follows:

$$C = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \cdots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix}, \quad a_{ij} = 1\,(i = 1, 2, \ldots, n),$$
$$C_i = \sum_{j=1}^{n}\left|a_{ij}\right| - 1, \quad i = 1, 2, \ldots, n. \quad (4)$$

Assuming that the index system has n indicators, the correlation coefficient is as follows.

Then, C_i represents the total influence of the i index on other (n-1) indices, and the weight of each index can be obtained by normalizing C_i:

$$\lambda = \frac{C_i}{\sum_{i=1}^{n} C_i}, \quad i = 1, 2, \ldots, n. \quad (5)$$

Finally, the symbiotic level of the high-tech industry innovation ecosystem depends on the symbiotic level of its symbiotic population. Therefore, the symbiotic degree of the high-tech industry innovation ecosystem can be obtained by a geometrically weighted integration of the symbiotic level of each symbiotic population.

$$\mathrm{DSM} = \prod_{i=1}^{n} \mathrm{dsm}_i\left(x_i\right)^{\omega_i}, \omega_i \geq 0, \sum_{j=0}^{n} \omega_i = 1. \quad (6)$$

In this formula, DSM is the symbiotic degree of the innovation ecosystem in the high-tech industry. When the DSM is greater, the symbiotic level of the innovation ecosystem is higher and vice versa. On this basis, the formula follows the principles of scientificity, reliability, representativeness, and availability and uses the research results of scholars at home and abroad for reference to select the symbiotic evaluation indices of the unit, matrix, platform, network, and environment to evaluate the symbiotic degree of the regional innovation ecosystem. Among them, the symbiotic units were evaluated by the three indicators of enterprises, universities, and research institutions directly involved in innovation activities. The symbiotic matrix was evaluated by the full-time equivalent of regional R&D personnel using the three indicators of the internal expenditure of regional R&D funds and the fixed asset investment of the whole society. The symbiosis platform was evaluated by four indicators: the number of national science and technology incubators, the average output value of high-tech industrial development zones, the average output value of characteristic industrial bases, and the average service income of national productivity promotion centers. The symbiotic network was evaluated by four indicators: the funding of universities and research institutes from the enterprise quota, the number of cooperative papers between authors in the region and different units in the province, the volume of technology market transactions in the region, and the Internet broadband access port in the region. The symbiotic environment was evaluated by regional per capita GDP, average years of education, regional public library collection, and retail sales of social consumer goods, resident consumption level, regional foreign technology imports, and actual utilization of foreign direct investment.

3.3.2. Evaluation Index of the Input Factors. To realize and improve the efficient symbiosis of various elements in the innovation ecosystem of the high-tech industry, the ecosystem needs various resource elements as inputs. These elements are embodied multidimensionally and include human, capital, material, technical, information, and knowledge resources [42]. Considering the strong substitution of various elements in explicit form and referring to relevant research results, this paper evaluated the input factors of the symbiotic efficiency evaluation of the high-tech industry innovation ecosystem from three symbiotic resource input aspects: human, capital, and material.

(1) Symbiotic personnel investment. The personnel input of the symbiotic system of the innovation ecosystem in the high-tech industry can be more apparent than the total and quality inputs of human resources. The total amount of human resource input was evaluated by the full-time equivalent of R&D researchers [43], and the quality of the human resource input was evaluated by the number of technical and economic employees [44].

(2) Symbiotic capital investment. The capital investment of the symbiotic system of the high-tech industry innovation ecosystem is mainly used for the symbiotic cooperation between the elements of the innovation ecosystem, which is mainly reflected in the innovation exchange and cooperation between different elements. Based on the symbiotic practice of the high-tech industry innovation ecosystem, this paper evaluated its capital investment by calculating the amount of technology, the number of technology market contracts, and the university capital source enterprises.

(3) Symbiotic material input. The material input of the symbiotic system of the high-tech industry innovation ecosystem is mainly reflected in the material elements of the innovation ecosystem. The symbiotic relationship is based on the number of species in various groups. Therefore, when the number of large-scale enterprises is greater, so are the technology demand, the technology supply in colleges, universities, and scientific research institutions, the number of intermediary institutions, and the probability of forming a symbiotic system [45]. This paper used the number of high-tech enterprises above scale; the total number of colleges, universities, and scientific research institutions; and the number of intermediary institutions to evaluate the material input in the symbiotic process of the high-tech industry innovation ecosystem [46].

The innovation environment is one of the elements of the industrial innovation ecosystem that is closely related to innovation activities within the system and is beneficial to the smooth development of innovation activities [47]. The innovation environment is the sum of external conditions that can affect the occurrence, survival, and evolution of high-tech industry innovation ecosystems. The characteristics of the high-tech industry determine the high risk of innovation ecosystems and the high degree of innovation environment change. A series of risks that need to be avoided, such as how to share the opportunity cost and sunk cost, make the marginal benefit greater than the marginal cost, reduce the uncertainty of the system environment, and increase the purpose of innovation activities, must be realized by forming a community of symbiotic interests. In addition to the direct impact of the input and output factors of the symbiotic system of the innovation ecosystem of high-tech industries on symbiotic efficiency, its symbiotic efficiency is also indirectly affected by factors such as economic development level and policy status. Based on the classical PEST theoretical framework, this paper analyzed the influencing factors of the symbiotic efficiency of the high-tech industry innovation ecosystem.

In terms of the symbiotic policy factors, industrial policy is the sum of various policies that the government uses to guide and promote the innovation and development of the high-tech industry. It has an important impact on regulating and promoting the symbiosis and coordinated development of elements in the innovation ecosystem of high-tech industries. Government policies can be evaluated by the number of relevant industrial policies.

In the process of influencing the symbiotic efficiency of the high-tech industrial innovation ecosystem, the symbiotic economic factors can be externalized in multiple dimensions, such as the economic development level and economic growth rate, and can have corresponding impacts on the symbiosis of a high-tech industrial innovation ecosystem in different ways and through different mechanisms. Considering that economic increments also transform into economic stocks and affect the symbiotic efficiency of the high-tech industry innovation ecosystem, GDP was selected to evaluate the economic factors.

Symbiotic social factors include the social system, groups, and interaction; moral norms; national laws; public opinion and customs; and other multidimensional factors. Particularly in the field of high-tech industry innovation ecosystem symbiosis, its symbiotic process mainly involves partner selection, interest distribution and constraint incentives, and other elements. Therefore, the social credit system plays a special important role in maintaining the relationship between the elements of the high-tech industry innovation ecosystem. Thus, the social credit index was selected to evaluate the social factors affecting the symbiotic efficiency of the high-tech industry innovation ecosystem.

Symbiotic technical factors are the basic factors supporting the symbiosis of the high-tech industry innovation ecosystem. These factors not only directly relate to the symbiotic level of various elements in the innovation ecosystem but also indirectly affect the symbiotic efficiency of various elements in the innovation ecosystem of the high-tech industry by influencing the development level of various elements. In particular, the technological interaction among the symbiotic elements in the innovation ecosystem of the high-tech industry can directly reflect and affect the symbiosis of system elements. Therefore, the number of organizational technology transfer activities was selected to evaluate the technical factors affecting the symbiosis of the high-tech industry innovation ecosystem.

In summary, the evaluation index system of output factors, input factors, and influencing factors of the symbiotic efficiency of the high-tech industry innovation ecosystem is shown in Figure 2.

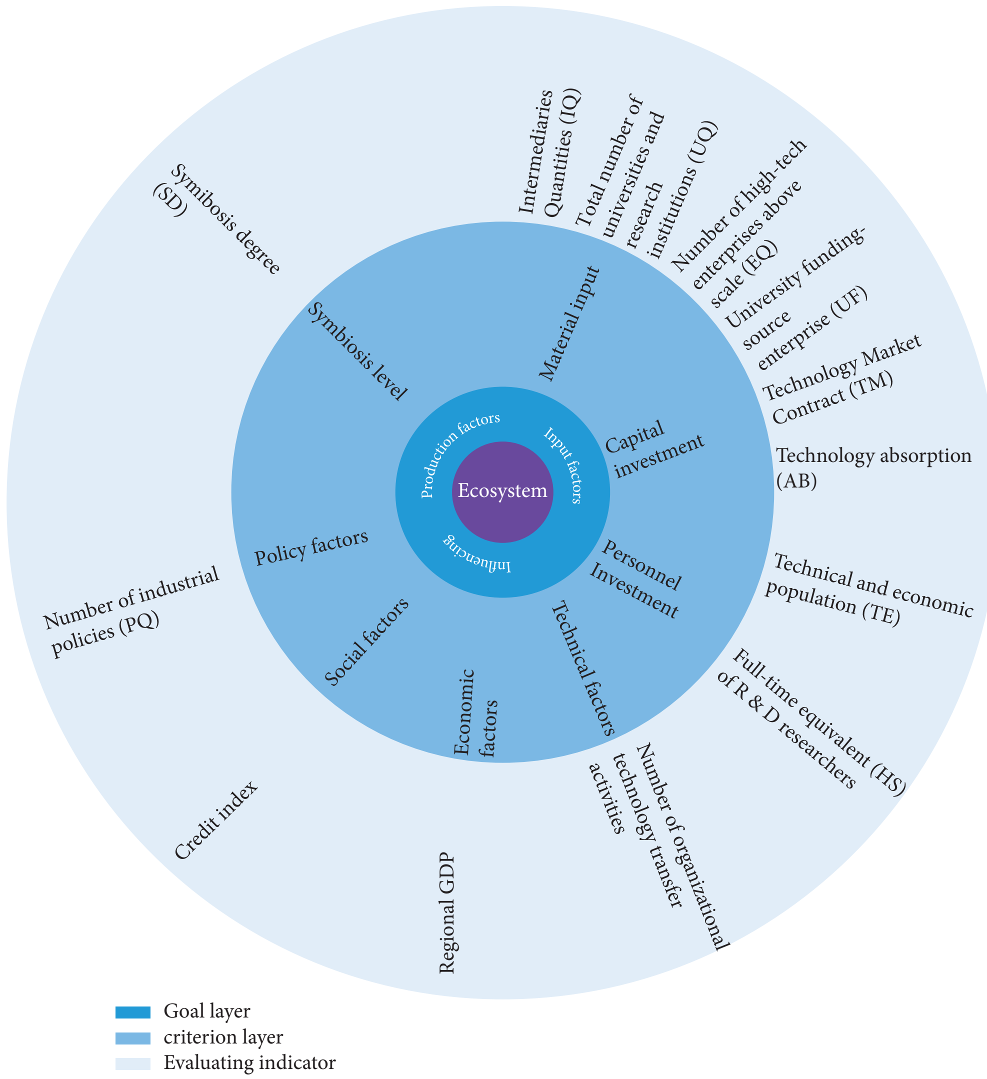

Figure 2: Evaluation index system of the symbiotic efficiency of the high-tech industrial innovation ecosystem.

4. Evaluation Model

4.1. SFA. In the SFA, the actual output formed by various inputs is compared with the maximum output that can be achieved in theory. Early researchers adopted the model shown in formula (7) for the SFA:

$$Y_{it} = \beta \bullet X_{it} + \varepsilon. \tag{7}$$

In this formula, Y_{it} and X_{it} represent the inputs and outputs, respectively. Since this method cannot effectively evaluate the technical inefficiency term ε, subsequent researchers divided ε into an inefficiency and a random error term; therefore, the model is shown as follows:

$$Y_{it} = \beta \bullet X_{it} + v_{it} - u_{it}. \tag{8}$$

In this formula, v_{it} and u_{it} are the random error and inefficiency terms, respectively; v represents the impact of large-scale uncontrollable factors; and u contains factors such as ineffective management, which can be used to evaluate the level of inefficiency.

The Cobb–Douglas or translog function is commonly used as the production function in an SFA. The logarithmic forms of the Cobb–Douglas function and translog functions are as follows:

$$\ln f = \beta_0 + \beta_1 \ln K + \beta_2 \ln L + v - u, \tag{9}$$

$$\ln f = \beta_0 + \beta_1 \ln K + \beta_2 \ln L + \beta_3 (\ln K)^2 + \beta_4 (\ln L)^2 + \beta_5 \ln K \ln L + v - u. \tag{10}$$

In these formulas, β_0 to β_5 are the constant and corresponding coefficients, respectively.

For the above model, the LR method can be used for testing, and the LR statistics can be expressed as

$$\begin{aligned} LR &= -2\ \ln\ \lambda, \\ &= -2\ \ln\left(\frac{L(\theta_0)}{L(\theta_1)}\right), \\ &= -2\ \ln\ L(\theta_0) + 2\ \ln\ L(\theta_1), \\ &= 2\times[\ln\ L(\theta_1) - \ln\ L(\theta_0)]. \end{aligned} \tag{11}$$

$L(\theta_0)$ and $L(\theta_1)$ are the likelihood function values when constrained and unconstrained, respectively. $LR \sim \text{mix}\chi_n^2$, that is, LR follows the distribution of χ^2 in the degree of freedom n.

We define the technical efficiency as follows:

$$\begin{aligned} TE_i &= \frac{q_i}{\exp(x_i\beta + v_i)}, \\ &= \frac{\exp(x_i\beta + v_i - u_i)}{\exp(x_i\beta + v_i)}, \\ &= \exp(-u_i). \end{aligned} \tag{12}$$

In this formula, x_i is used to represent the input of the high-tech industrial innovation ecosystem i. β is the parameter that needs to be measured. q_i is the output of the high-tech industrial innovation ecosystem i. v_i is the random error term, and u_i is the technical invalid term. Therefore, when u_i is smaller, the efficiency is higher and vice versa.

4.2. Theoretical Model Design for the Symbiotic Efficiency Evaluation. Based on the advantages of the Cobb–Douglas production function with an intuitive economic meaning and a high accuracy, this paper constructed a symbiotic efficiency evaluation model of the high-tech industry innovation ecosystem without considering the influencing factors, as shown in the following formula:

$$\begin{aligned} \ln\ SD_{it} = {} & \beta_0 + \beta_1 \ln\ HS_{it} + \beta_2 \ln\ TE_{it} + \beta_3 \ln\ AB_{it} + \beta_4 \ln\ TM_{it} + \beta_5 \ln\ UF_{it} \\ & + \beta_6 \ln\ EQ_{it} + \beta_7 \ln\ UQ_{it} + \beta_8 \ln\ IQ_{it} + V_{it} - U_{it}. \end{aligned} \tag{13}$$

In this formula, SD_{it}, HS_{it}, TE_{it}, AB_{it}, TM_{it}, UF_{it}, EQ_{it}, UQ_{it}, and IQ_{it} denote the symbiotic degree of the high-tech industrial innovation ecosystem in region i during period t, the full-time equivalent of R&D researchers, the number of technical and economic personnel, the amount of technology absorbed, the amount of technology market contracts, the portion of university funding sources, the number of high-tech enterprises above a designated size, the total number of universities and research institutions, and the number of intermediary institutions, respectively. V_{it} represents a random error item associated with statistical noise. Assuming $V_{it} \sim N(0,\sigma_v^2)$, U_{it} represents the management invalid term and obeys the non-negative truncated normal distribution, that is, $U_{it} \sim N^+(u,\sigma_u^2)$. Battes designed variance parameters $\gamma = \sigma_u^2/(\sigma_v^2 + \sigma_u^2)$ to test the proportion of technical inefficiency in disturbances, $0 \le \gamma \le 1$. Its value was estimated by the maximum likelihood method. When $\gamma = 0$, the gap between the actual output and the frontier production surface mainly comes from the random error. At this time, the least square method was used for the estimation, without the use of SFA technology.

Based on the above model, this paper constructed a symbiotic efficiency evaluation model of a high-tech industrial innovation ecosystem considering the influencing factors, as shown in the following formula:

$$\begin{aligned} SD_{it} = {} & \alpha_0 + \alpha_1 HS_{it} + \alpha_2 TE_{it} + \alpha_3 AB_{it} + \alpha_4 TM_{it} + \alpha_5 UF_{it} + \alpha_6 EQ_{it} + \alpha_7 UQ_{it} \\ & + \alpha_8 IQ_{it} + \alpha_9 PQ_{it} + \alpha_{10} G\ DP_{it} + \alpha_{11} CI_{it} + \alpha_{12} TT_{it} + \alpha_{13} T. \end{aligned} \tag{14}$$

In this formula, the meanings of SD_{it}, HS_{it}, TE_{it}, AB_{it}, TM_{it}, UF_{it}, EQ_{it}, UQ_{it}, and IQ_{it} are the same as above. PQ_{it}, $G\ DP_{it}$, CI_{it}, and TT_{it} denote the policy, economic, social, and technical influencing factors, respectively, of the high-tech industry innovation ecosystem in region i during period t.

To ensure the effectiveness of the measurement model, the maximum likelihood estimation method was used. The gamma values were highly significant, and the LR statistical test was significant at the 5% significance level, thus ensuring the effectiveness of the evaluation model constructed in this paper.

5. Empirical Research

5.1. Object Selection. This paper first tests the effectiveness of the symbiotic efficiency evaluation system of a previously constructed high-tech innovation ecosystem. Second, this paper reveals the current situation and laws of the symbiotic efficiency of China's high-tech industry innovation ecosystem and designs a strategic system for improving it. Therefore, the selection of empirical objects in this paper should focus on the main body of the high-tech innovation ecosystem. The innovation ecosystem of the high-tech industry is complex and perfectly symbiotic. Each innovation subject in the high-tech industry creates value through collaborative innovations with other subjects by exerting its own heterogeneity, resulting in an interdependent and symbiotic innovation ecosystem. This innovation ecosystem is a multidimensional complex network structure with high-tech enterprises as the core subject and universities, scientific research institutions, governments, financial institutions, and intermediary service institutions as the system elements. Therefore, empirical research on the operational efficiency of high-tech innovation ecosystems should focus on the selection of empirical research objects around the core element of the high-tech industry.

According to the official statistical yearbook (China Statistical Yearbook 2020), there are 169 national high-tech industrial parks. A large number of high-tech enterprises and related supporting organizations are concentrated in these high-tech industrial parks, with wide industry coverage and strong high-tech attributes. They have the basic conditions constituting the innovation ecosystem of the high-tech industry. Selecting national high-tech industrial parks as the empirical object has the following advantages:

First, the purity of the core population of the innovative ecological system is ensured. In the innovation ecosystem of the high-tech industry, the core enterprises are the starting point of innovation activities and the central node of the whole ecosystem. When selecting empirical objects, the influence of nonhigh-tech enterprises should be eliminated as much as possible. The selected core enterprises must have strong high-tech attributes. In national high-tech industrial parks, both high-tech enterprises and industries can achieve balance and coverage. At the same time, the incubators in the industrial park can continuously and dynamically adjust the core population size by adjusting the number of incubated and graduated companies. Doing so is conducive to ensuring the purity of the enterprise population in the innovation ecosystem of the high-tech industry.

Second, the adequacy of the main components of the innovation ecosystem is ensured. At the same time, a symbiotic network is composed of horizontal and vertical links between multiple innovation subjects. Other group roles are equally important. After years of operation and development in the national high-tech industrial park, mature supporting enterprises, research institutions, and intermediary populations have been formed in and around it. The government also has a relatively clear policy support system and credit evaluation system for the development of the high-tech industry, which provides a natural advantage in ensuring the integrity of the main component of the innovation ecosystem.

Third, the integrity of the structure of the innovation ecosystem is guaranteed. The innovation ecosystem differs from traditional innovation systems in that it fully considers the impact of environmental communities on biological communities and their interactions with each other. Both the human and natural environments have an important impact on the innovation ecosystem. National high-tech industrial parks are subject to geographical constraints, and both the environment and policy have obvious differences. The regional environment can directly affect the abundance of innovation factors such as the establishment cost of supporting enterprise relationships, the acquisition and reserve of innovative production resources, and the attraction of innovative talent. The government also has an important impact on industry development. Through policy formulation and other rewards and punishments, it objectively has a direct and indirect impact on the operation of the innovation ecosystem. Environmental factors were fully considered in the empirical study of the innovation ecosystem, and they improved the structural integrity of the innovation body system of the high-tech industry [48].

Fourth, the richness and rigors of the index selection are ensured. In the empirical process, the scientific nature and availability of the index selection are the principles that must be adhered to. Compared with the unclear and generalized statistical indicators of simple industries, national high-tech industrial parks have more detailed and accurate indicators available through different yearbooks, such as the "high-tech industry yearbook" and "torch yearbook." This availability enriches the index system selection and broadens its scope. It also provides a guarantee for the realization of the directivity and precision of the index selection in the empirical research, improves the operability of the research on the operation efficiency evaluation of the innovation ecosystem of the high-tech industry, and improves the pertinence and meticulousness of this research. This can lead to more scientific and rigorous studies on the operational efficiency evaluation of the innovation ecosystem of the high-tech industry on the basis of existing research. Therefore, this paper selected empirical research objects based on the national high-tech industrial park.

5.2. Calculation and Analysis of Symbiotic Efficiency. To calculate the symbiotic efficiency of the high-tech industry innovation ecosystem, the symbiotic degree of 30 high-tech industry innovation ecosystems in China was measured using the model constructed above, and the results are shown in Figure 3.

The analysis of the measurement results of the symbiotic degree of the innovation ecosystem of the high-tech industry indicated the following conclusions. First, overall, the symbiotic

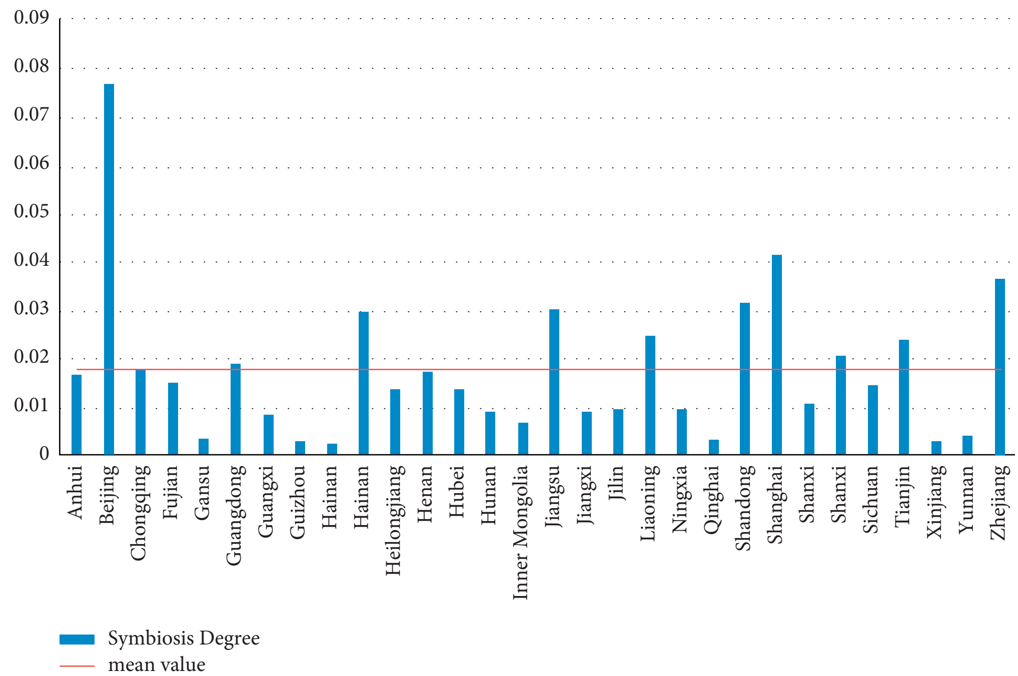

Figure 3: Symbiotic degree of 30 high-tech industry innovation ecosystem in China.

Table 1: Comparison of symbiotic efficiency between considering and without considering the influencing factors.

Region	Without considering the influencing factors	Considering the influencing factors	Region	Without considering the influencing factors	Considering the influencing factors
Anhui	0.91645	0.91828	Jiangsu	0.90754	0.90845
Beijing	0.98367	0.98465	Jiangxi	0.91989	0.92081
Chongqing	0.66165	0.66297	Liaoning	0.67866	0.6807
Fujian	0.67661	0.67864	Inner Mongolia	0.50378	0.50479
Gansu	0.61731	0.61793	Ningxia	0.18385	0.1844
Guangdong	0.84118	0.8437	Qinghai	0.10868	0.1089
Guangxi	0.77076	0.77153	Shandong	0.97451	0.97646
Jilin	0.86957	0.87044	Shanxi	0.51808	0.5186
Guizhou	0.61806	0.61868	Shanxi	0.96533	0.96823
Hainan	0.23489	0.23512	Shanghai	0.98661	0.98957
Hebei	0.68746	0.68952	Sichuan	0.80581	0.80823
Henan	0.61841	0.62027	Tianjin	0.47638	0.47733
Heilongjiang	0.85594	0.85765	Xinjiang	0.85736	0.85822
Hubei	0.9731	0.97407	Yunnan	0.83086	0.83252
Hunan	0.89698	0.89877	Zhejiang	0.81562	0.81644

level of the elements of the innovation ecosystem of high-tech industries in China was still low, and the average degree of the symbiosis in the 30 regions was only 0.01760. This result showed that the symbiotic level of the elements of the innovation ecosystem of the high-tech industry in China still had much room for improvement. Second, looking at specific regions, the symbiotic level of the high-tech industrial innovation ecosystem in economically developed provinces and cities such as Beijing, Shanghai, Zhejiang, Shandong, and Jiangsu was relatively high. Meanwhile, the symbiotic levels in underdeveloped regions such as Hainan, Guizhou, Xinjiang, Qinghai, and Gansu were relatively low. The results showed that the symbiotic level of a high-tech industrial innovation ecosystem was highly and positively correlated with the level of regional economic development. Finally, the symbiotic degree of the high-tech industry innovation ecosystem differed greatly among Eastern, Central, and Western China. Eastern China had the highest symbiotic degree of 0.03014, Western China had the lowest at 0.00858, and Central China had a symbiotic degree of 0.01254. The results were highly consistent with the ladder distribution of China's economic development.

The symbiotic degree of the high-tech industry innovation ecosystem was measured. This paper used the above model to calculate the symbiotic efficiency of the high-tech industry innovation ecosystem in 30 regions of China without considering the influencing factors. On this basis, the above model was used to further calculate the symbiotic efficiency of the high-tech industry innovation ecosystem in China's 30 regions considering the influencing factors, and the compared results are shown in Table 1.

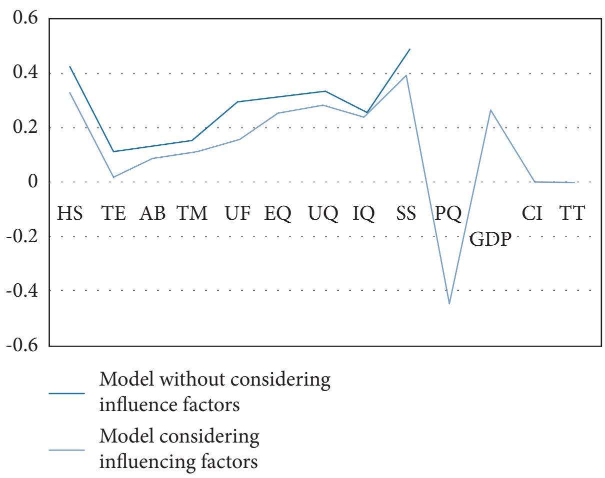

Figure 4: Calculation results of influence level of efficiency factors in symbiotic of high-tech industrial innovation ecosystem.

5.3. Calculation and Analysis of the Influencing Factors. The calculation results are given of the influencing factors of the symbiotic efficiency of a high-tech industrial innovation ecosystem. The analysis of the measurement results of the influencing factors of the symbiotic efficiency of the high-tech industry innovation ecosystem indicated that the input and influencing factors had heterogeneous effects on the symbiotic efficiency of the high-tech industry innovation ecosystem in Figure 4.

6. Discussion and Conclusion

Based on the above analysis results of the symbiotic efficiency, we propose three major conclusions.

First, there is a large degree of dispersion and nonequilibrium in the symbiotic efficiency of China's high-tech industry innovation ecosystem. Whether the influencing factors are considered or not, only the symbiotic efficiency of Shanghai and Beijing exceeds 0.98. The symbiotic efficiency of the last two, Qinghai and Ningxia, is less than 0.2. It can be seen that the symbiotic efficiency gap between advanced regions and backward regions has reached 908%, indicating that there is a large degree of discretization and nonequilibrium in the development of high-tech industrial innovation ecosystems and their efficiency in different regions of China.

Second, the symbiotic efficiency improvement of China's high-tech industrial innovation ecosystem is gradually increasingly difficult. Regardless of whether the influencing factors are considered or not, the median symbiotic efficiency of China's high-tech industry innovation ecosystem is above 0.8. The results show that the symbiotic efficiency of the innovation ecosystem of high-tech industries in most parts of China exceeds the national average. It can be inferred that when the symbiotic efficiency of the innovation ecosystem of high-tech industries reaches a certain level, its difficulty of improvement will gradually increase.

Third, the symbiosis efficiency of China's high-tech industrial innovation ecosystem, the symbiosis of the high-tech industrial innovation ecosystem, and the degree of regional economic development are not significantly correlated. Through comparative analysis, it can be found that the symbiosis of high-tech industrial innovation ecosystems in Hubei and Anhui is not prominent, but its symbiosis efficiency is high, indicating that the abovementioned regions can transform relatively small symbiotic resource inputs into effective co-production; on the contrary, although the symbiosis of high-tech industrial innovation ecosystems in Tianjin, Hebei, and Liaoning is high, its symbiosis efficiency is relatively low, indicating that there is a problem of low efficiency in the transformation of symbiotic resource inputs in the above regions. The results are in line with Anhui's development status of "focusing on building a comprehensive national science center and industrial innovation center with important influence, building a comprehensive national science center, continuous growth of innovation indicators, accelerated convergence of various talents, the emergence of original achievements, remarkable industrial innovation results, and an increasingly strong atmosphere of innovation," as well as Tianjin's regional development practices such as "investment-dependent economic growth mode, heavy industry as the absolute mainstay, and industry overcapacity."

This study has the following implications: (1) we should pay full attention to the role of scientific research institutions in the innovation ecosystem. Through research, we found that the number of scientific research institutes and the quality of talents provided have an important positive impact on symbiotic efficiency, so it is necessary to strengthen the construction and investment of scientific research institutions in regional construction. (2) It is necessary to pay attention to the development of school-enterprise cooperation. It is found that the funds of source enterprises in universities obviously promote symbiotic efficiency, so it is necessary to actively strengthen the cooperation between universities and enterprises and accelerate the flow of funds and technology in the symbiotic system. (3) We should be fully aware of the environmental impact. The different policies and regional environments may play a leading role in symbiotic efficiency, and especially policies may also play a role in inhibition, so it is necessary to pay enough attention to the creation of a regional innovation environment.

In the study, although the high-tech parks have been selected as the case study object as much as possible, there may still be insufficient sample size, and especially the imbalance of economic development between regions is likely to cause a prepotential impact on this study. In addition, there may still be a situation that is not comprehensive and reasonable regarding the selection of influencing factors. For future research, the breadth and depth of research can be improved from the perspective of expanding the selection of research objects and the comprehensive application of multiple efficiency evaluation methods.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The author declares that there are no conflicts of interest.

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