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Article

STI or DUI modes of innovation: Evidence from comprehensive evaluation of four cities in China

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Abstract: The Science and Technology Innovation Center holds a pivotal position in the national science and technology innovation system, and a scientific evaluation of the "Sci-tech Innovation Center" will guide its construction direction. This study found the advantages and disadvantages of the four cities through comparison; Hence improvement suggestions were proposed for the weaknesses of the four cities. There are two main paths for the government to drive technology innovation: STI (Science and Technology Innovation) mode and DUI (Doing, Using, Interacting) mode. With the aid of the evaluation index system of the Sci-tech Innovation Center, this article uses fuzzy sets, rough sets and fuzzy dynamic clustering methods to comprehensively evaluate the effects of driving technology innovation in the four cities of Beijing, Shanghai, Shenzhen and Guangzhou. The results found that Shenzhen has a significant effect in DUI, and Beijing has a significant effect in STI. The choice of path is related to the abundance of innovation resources.

Keywords: Sci-tech Innovation Center; rough sets; fuzzy sets

1. Introduction

On 21 July 2021, the National Development and Reform Commission of China issued a notice on promoting and drawing on the innovative measures and practices of the Shenzhen Special Economic Zone, in which the innovation experience of the entire process of innovation ecological chain management in Shenzhen is recommended as a key content. This indicates that the relevant departments of the country intend to promote the construction of the whole process innovation ecological chain nationwide, and Beijing, Shanghai, Guangzhou, and Shenzhen, which have also set the goal of becoming global science and technology innovation centers, should be the main force and leader in the construction of the whole process innovation ecological chain at the national level. Therefore, it is of great significance to study how to promote collaborative technological innovation among the four cities, integrate them into China's national level innovation ecosystem, and jointly promote the improvement of the national scientific and technological innovation system.

There are two basic paths for driving technology innovation. One path is starting from basic research, going through applied basic research, applied research and industrialization research, and finally creating market demand. During this course of driving technology innovation, the key participator to achieve this goal are scientists, and this driving model is the STI (Science and Technology Innovation) model; The other path starts from the market demand, and when enterprises encounter application technical problems in the process of developing products to meet the market demand, they feed back to the application and basic research field. During this course of driving technology innovation, the key participator to achieve this goal are entrepreneurs. This model is called the DUI (Doing, Using, Interacting) model (Santos et al., 2022). Based on the significant differences in innovation on the two paths, it can be inferred that the resources required to drive innovation on different paths are also different. Therefore, should the government focus on STI mode innovation, DUI mode innovation, or both? The existing evaluation index system for science and technology innovation centers is an evaluation of the entire system. This article attempts to draw on the evaluation index system of science and technology innovation centers to compare the effectiveness of government driven innovation in the four cities of Beijing, Shanghai, Shenzhen, and Guangzhou, in order to find suitable directions for the government to formulae reasonable policies to drive innovation. At present, there are several evaluation index systems for Sci-tech Innovation Centers in the world, including two evaluation index systems publicly released in China in recent years. These evaluation index systems have different focuses. Some focus on the urban innovation investment environment, some on the urban innovation cultural environment, some on the urban Sci-tech R&D capability (Deng et al., 2019), Some focus on basic research capacity. The evaluation index system of Sci-tech Innovation Center constructed in this paper makes innovation in the following three aspects: first, the evaluation index system is designed to test the effect of government-driven Sci-tech innovation; Secondly, it introduces regional influence, national influence and international influence to interpret the evaluation of “Sci-tech Innovation Center” more comprehensively and systematically. Third, the weighting of evaluation indicators is achieved by using fuzzy rough set method and data itself, which avoids the artificial interference of weighting.

The rest of the article is arranged as follows. Section 2 reviews the literature on comprehensive evaluation of Sci-tech Center. Section 3 constructions Sci-tech Innovation Center evaluation index system. Section 4 presents our analysis and discussion according to the results. Section 5 provides policy recommendations. Section 6 draws our conclusion.

2. Literature review

2.1. The literatures about Sci-tech Innovation Centers

Since the concept of “Global hubs of technological innovation” was put forward by Online magazine in July 2000, the academic circle has conducted extensive and in-depth research on the concept, connotation, characteristics and evaluation of technological innovation centers. However, what kind of area is the Sci-tech Innovation Center and what characteristics does it have? There is no consensus yet. Sci-tech Innovation Centers are characterized by main body diversity and strong inclusiveness, especially in the joint participation and interaction of research universities, research institutions, private investors and the public sector (Geenhuizen and Soetanto, 2008). It is found that the center of technology innovation contains institutions such as universities, research centers, consulting institutions, local government agencies, intermediaries and enterprises, and the diversity of its institutions is its main characteristic (Ritala et al., 2015). The Sci-tech Innovation Centers have different characteristics in different development stages (Xiong, 2015). Five prominent features of global Sci-tech Innovation Centers were summarized: functional dominance, structural hierarchy, spatial agglomeration, industrial high-end, and cultural inclusiveness (Du and He, 2016). The Sci-tech Innovation Center is composed of science center, technology center and industry center, the formation of these centers are influenced by much factors (Huang and Feng, 2018). The Sci-tech Innovation Center can be considered a high-end agglomeration of innovation resources, the original innovation ability, radiation lead ability, and strong innovation culture, obvious innovation driving effect, and the dominant in the global sci-tech innovation city or metropolitan area, is the new ideas, new knowledge, new technology, new products, new forms and new model of origins (Zhang et al., 2018). The global Sci-tech Innovation Center is a city or region that occupies a leading and dominant position in the global sci-tech innovation activities. It has the characteristics of intensive sci-tech innovation resources, active innovation activities, strong innovation ability and extensive innovation influence (Sui, 2020). From the analysis of the global famous Sci-tech Innovation Center, it has the following characteristics: high strength of R&D, agglomeration of high-level scientific research institutes of technology, through “government, industry, enterprise” the innovation of the ecological system, to attract global innovation talent and present a multicultural background, abundant of venture capital and “innovation” of doing business (Li and Luo, 2021). These characteristics become the basis of the evaluation index system of the Sci-tech Innovation Center in this paper.

2.2. The literatures about evaluation index system of Sci-tech Innovation Center

Chen (2016) constructed the evaluation index system of “global Sci-tech Innovation Centers”, which has 8 primary indicators, 22 secondary indicators and 89 tertiary indicators, but no weighting for the indicators. This paper uses this literature as the important basis of research. Zhang (2017) constructed an evaluation index system for Sci-tech Innovation Centers using agglomeration function, originality function, driving function, radiation function, and dominant function as secondary indicators and 28 tertiary indicators. With reference to the relevant research report of PricewaterhouseCoopers on “Cities of Opportunity”, Deng et al (2019) constructed a global Sci-tech Innovation Center evaluation index system with three primary indicators and eight secondary indicators based on entropy-weighted TOPSIS. Other publicly released and more influential global Sci-tech Innovation Center evaluation rankings include: the Global Innovation City Index by Australian think tank 2thinknow (Li et al., 2019); the Global Sci-tech Innovation Center Assessment Report published by Shanghai Municipal Information Center since 2018, ranking Beijing, Shanghai, Shenzhen, Hong Kong and Guangzhou 6th, 9th, 18th, 20th and 39th respectively in 2021 (Jin, 2021); the Global Sci-tech Innovation Center Index jointly published by Springer Nature and Tsinghua University since 2020, Beijing, Shanghai, Hong Kong and Shenzhen are ranked 5th, 17th, 22nd and 25th in the world in 2020, respectively, and Guangzhou is not included in the evaluation (Anonymous, 2020).

The existing index systems for evaluating Sci-tech Innovation Centers have their own focus, and the ranking of the same city in different evaluation systems varies greatly. In this paper, based on absorbing the advantages of these indicator systems, we evaluate the effectiveness of government-driven sci-tech innovation in four cities in Beijing, Shanghai, Shenzhen and Guangzhou, and provide evidence for finding effective driving paths. Most of the existing literature mainly analyzes the effects of specific innovation policies of the government. Including but not limited to public subsidies, tax incentives, grants, low-interest loans, infrastructure building, public procurement, had been researched on how these policy instruments adopted by governments foster innovation (Aschhoff and Sofka, 2009; Bronzini and Piselli, 2016; Cheng, 2020; Dimos and Pugh, 2016). However, there are few literatures evaluating the overall effects of innovation policies in a region, which will be explored in this paper.

3. Construction Sci-tech Innovation Center evaluation index system

3.1. Determine and define the initial set of evaluation metrics

3.1.1. Initial evaluation indicators

The rough set proposed by Polish mathematician Pawlak (1982) and the fuzzy set proposed by Zadeh (1965), are two important methods to study the problem of incomplete and uncertain information in information systems. In view of the fact that these Chinese cities statistical data collected in this paper contains fuzzy, incomplete and uncertain information, we choose to construct the evaluation index system of Sci-tech Innovation Center based on fuzzy rough set theory, expecting to get more objective and reasonable evaluation results by “letting the data speak for themselves”.

Based on the evaluation index system of “global Sci-tech Innovation Center” constructed by Chen (2016), 194 evaluation indicators are obtained by combining the results of hundreds of related research papers with high reference value and consulting with relevant experts (for the specific definition of each index, please refer to the relevant references).

3.1.2. Sources of evaluation data

The actual or calculated values of the indicators were obtained by consulting the “China National Statistical Bulletin” “China National Statistical Yearbook” “China Torch Statistical Yearbook” “China Business Yearbook” “China City Statistical Yearbook”, the statistical bulletins and statistical yearbooks of Beijing, Shanghai, Guangzhou and Shenzhen, as well as the official websites of “Chinese Academy of Social Sciences”, “Torch Center of Ministry of Science and Technology” and “Qingke Database” from 2014 to 2019, and then the information table of the actual values was generated (omitted).

3.1.3. Using correlation analysis to reject part indicators

SPSS software was used to analyze the correlation of the indicators, and the Pearson Correlation coefficient value of 0.968 was set as the threshold value to eliminate the redundant indicators with too high correlation (the value of Pearson Correlation coefficient with other indicators is above the threshold value). The principles of systematicity, completeness, hierarchy, dynamism, objectivity, comparability, substitutability, and accessibility are followed (e.g., considering the principles of substitutability and accessibility, the data of "Internet broadband subscribers and cell phone subscribers" is used to represent "5G/4G subscriber penetration rate", and considering the principles of objectivity, comparability and substitutability, the relative indicator of "the proportion of PCT international patent applications in the country" is used, and the absolute indicator of "the number of PCT international patent applications" is excluded). The initial indicator set of the evaluation of Sci-tech Innovation Center is obtained. (Initial domain set: 87 evaluation indicators)

3.2. Construction of evaluation indicator system

Fuzzy clustering is a multivariate technique that uses fuzzy mathematical methods to classify objective things by establishing fuzzy similarity relationships based on the characteristics, closeness and similarity between them, and has been widely used and effective in many Sci-tech fields (Huang and Zhang, 2004). The dynamic clustering method can improve the classification, make the final kernel and approximation more accurate, remove the influence of interference information, and improve the correct rate of recognition while ensuring accuracy (Song, 2010). For this reason, we construct the evaluation indicator system of Sci-tech Innovation Center based on fuzzy dynamic clustering method.

3.2.1. Theoretical description

Let $X = (1,2,\cdots)$ be all the classified objects, and each object x_i is characterized by a set of data $(x_{i1},\ x_{i2},\ldots\ x_{im})$, to establish a fuzzy relationship on X (fuzzy similarity matrix) $R = \left(r_{ij}\right)_{n\times m}$, to express the similarity between x_i and x_j. Next, establish similarity matrix to find its transfer closure, i.e., using the flat method, compute $R \to R^2 \to R^4 \to \cdots \to R^{2^k} \to \cdots$, until the first time getting $R^{2^k} = R^{2^{k+1}}$, at which time $R^{2^k} = t(R)$ is the fuzzy equivalence matrix. Finally, we can obtain a clustering diagram by classify the equivalence relation truncated the value of elements from 1 to 0 in the fuzzy equivalence matrix $t(R)$.

3.2.2. Step

Step 1: to find the feature set Cr_i

A questionnaire survey of indicator classification was conducted to eight experts in professional fields for the correlations of 87 evaluation indicators and eight category indicators (innovation resources, innovation industries, innovation inputs, innovation carriers, innovation results, innovation culture, innovation entrepreneurship, and innovation impact (Chen, 2016)) initially screened. Among them, the numbers 9, 7, 5, 3, and 1 indicate especially relevant, very relevant, generally relevant, not very relevant, and not relevant, respectively. For example, if the experts think that the evaluation indicator "the proportion of PCT international patent applications in the country" and the category indicator "innovation achievements" are especially relevant, then fill in the number 9. The feature set Cr_i $(\mathrm{i} = 1,2,\cdots 87)$ of each indicator is obtained by simple averaging method based on the scores of the experts.

Step 2: to construct fuzzy similarity matrix R

According the absolute value subtraction method Equation (1), take the fuzzy similarity coefficient $c = 0.045$, construct fuzzy similarity matrix $R = \left(r_{ij}\right)_{n\times m}$ （i, j =l,2,⋯87）, among them $r_{ij} = r_{ji}$.

$$r_{ij} = \begin{cases} 1 & \text{when } i = j \\ 1 - c\sum_{k=1}^{m}\left|x_{ik} - x_{jk}\right| & \text{when } i \neq j \end{cases} \quad (1)$$

Step 3: to construct fuzzy equivalence matrix $t(R)$

Using the method of taking the smaller first and then the larger, i.e.,

$$R^2 = R\odot R = \left\{max\left[min\left(r_{im}, r_{mj}\right)\right]\right\} \quad (2)$$

Among them, i, j, m =l,2,⋯87.

After calculation, we can get fuzzy equivalence matrix: $R^{32} = R^{16}\odot R^{16} = R^{16} = t(R)$.

Step 4: to select different intercept values λ, and perform dynamic clustering on $t(R)$

When $0.89 \leq \lambda < 0.90$, can be divided into 60 categories, when $0.87 \leq \lambda < 0.88$, can be divided into 40 categories; when $0.85 \leq \lambda < 0.86$, can be divided into 21 categories; when $0.83 \leq \lambda < 0.84$ can be divided into 9 categories (Specific categories omitted).

Step 5: to construct evaluation indicator system

Select $0.85 \leq \lambda < 0.86$ as the intercept value of dynamic clustering of evaluation indicators and considering the possible results of dynamic clustering of several other categories, the evaluation indicator system of Sci-tech Innovation Center is constructed, as shown in Appendix **Table A1**, with 8 primary indicators, 26 secondary indicators and 87 tertiary indicators.

3.3. Determine the evaluation index weights based on fuzzy rough set theory

The basic idea of assigning weights to indicators based on the rough set and fuzzy set theory is to first carry out fuzzy clustering according to the used feature attributes, find the optimal classification, and consider it as a classification of some decision attributes to get the decision attributes which according to some hypothetical K equivalence set. According to the same method, individual attributes are sequentially deleted c_i and perform fuzzy clustering again, so as to obtain equivalence attributes for the conditional attribute $r_{C-c_i}(D)$. Then compute the dependency degree between conditional attributes and decision attributes $r_{C-c_i}(D)$, to obtain the importance degree of the attribute c_i. Finally, the weights of the factors are solved by using the normalized importance degree method.

3.3.1. Theoretical description

Definition 1. *Given a knowledge base* $K = (U, R)$, *for each subset of* $X \subset U$, *the equivalence relation* $R \subset ind(K)$, *call* $R\_(X) = \cup\{Y_i \subset |ind(R): Y_i \subset X\}$ *as the set of* R *lower approximations of* X.

Definition 2. *The dependency degree* $r_C(D)$ *of the two attributes set* C *and* D *is defined as:*

$$r_C(D) = card\big(pos_C(D)\big)/card(U) \tag{3}$$

here, $card(*)$ *denotes the set base,* $pos_C(D) = C - (D)$.

Definition 3. *The property* $a \in C$, *then the importance degree of properties* a *on* D *is defined as:*

$$SGF(a, C, D) = r_C(D) - r_{C-\{a\}}(D) \tag{4}$$

here $r_{C-\{a\}}(D)$ *indicates the dependence degree of the condition attributes on decision attributes after missing attribute* a *in* C.

3.3.2. Steps

Step 1: Generate real-value information tables and standardized them

Collect the 2018-year data, and generate the real-value information tables according to the previously identified and defined indicator set and its domain set. Then use the following formula to standardize the real-value information of each indicator, as shown in Appendix **Table A1**.

$$y_{ij} = x_{ij}\Bigg/\left(\sum_{i=1}^{n} x_{ij}^2\right)^{\frac{1}{2}} \tag{5}$$

Step 2: Determine the indicator weights and compute the weight value

When the survey sample is small and the evaluation indicators is more, such as these four samples and 87 indicators in this paper, it is more difficult to achieve directly with rough set to assign a weight to the indicator. This paper draws on the research results of Ding (2008). First, cluster the 87 tertiary indicators under 8 primary indicators with a rough set method for the survey sample, each tertiary indicators forms a different set under their own primary indicators, and carry out rough set index clustering through selecting different cut-off values. Then, solve the importance degree of each attribute (tertiary indicators); determine the weight of each tertiary indicators under each primary indicator. Finally, the weighting value of each object (Beijing, Shanghai, Guangzhou and Shenzhen) under each primary indicator are determined.

1) Assign a weight for the primary indicator “innovation resource” as an example, as following:

Order $K_1 = (U, A_1)$, here, $U = \{y_{\mathrm{bj}}、y_{\mathrm{sh}}、y_{\mathrm{sz}}、y_{\mathrm{gz}}\}$

$A_1 = \{x_1、x_2、x_3、x_4、x_5、x_6、x_7、x_8、x_9、x_{10}、x_{11}、x_{12}、x_{13}\}$

(1) Hierarchical clustering

First, select $0.9425 \le \lambda$ as the intercept value of the survey sample clustered dynamic, while sequentially removing the conditional attributes x_i $(i = 1,2,\cdots,13)$, the clustering results are obtained respectively as follows, and the specific clustering steps are as described previously. (Note: bj = Beijing; sh = Shanghai; sz = Shenzhen; gz = Guangzhou)

$$E_1(0.9425) = \{y_{\text{bj}}、y_{\text{sh}}\}、\{y_{\text{sz}}\}、\{y_{\text{gz}}\};$$

$$E_{1-x_1}(0.9425) = E_{1-x_3}(0.9425) = E_{1-x_4}(0.9425) = E_{1-x_6}(0.9425) = E_{1-x_7}(0.9425) = E_{1-x_8}(0.9425) = \{y_{\text{bj}}、y_{\text{sh}}、y_{\text{sz}}、y_{\text{gz}}\};$$

$$E_{1-x_2}(0.9425) = \{y_{\text{bj}}、y_{\text{sh}}、y_{\text{gz}}\}、\{y_{\text{sz}}\};$$

$$E_{1-x_5}(0.9425) = E_{1-x_9}(0.9425) = E_{1-x_{10}}(0.9425) = E_{1-x_{11}}(0.9425) = E_{1-x_{12}}(0.9425) = E_{1-x_{13}}(0.9425) = \{y_{\text{bj}}、y_{\text{sh}}、y_{\text{sz}}\}、\{y_{\text{gz}}\};$$

(2) Solve for the importance degree of each attribute using the rough set relevant principle

Solve separately for union set of the lower approximation sets of each equivalent set of the decision attributes, the following formula:

$$pos_{C-\{c_i\}}(D) = \{C - \{c_i\}\} - (D) = \cup \left\{\{C - \{c_i\}\} - Y_l\right\} \ (1 \le l \le s) \tag{6}$$

According to the Equations (3), (4) and (6), it can be calculated that the importance degree of factor x_1 as follow:

$$SGF(x_1, C, D) = r_C(D) - r_{C-\{x_1\}}(D) = 2/4 - 0/4 = 0.5.$$

By the same token, the importance degree of several other factors can be calculated as follow:

$$\begin{aligned} SGF(x_2, C, D) &= SGF(x_5, C, D) = SGF(x_9, C, D) = SGF(x_{10}, C, D) \\ &= SGF(x_{11}, C, D) = SGF(x_{12}, C, D) = SGF(x_{13}, C, D) \\ &= 2/4 - 1/4 = 0.25 \end{aligned}$$

$$\begin{aligned} SGF(x_3, C, D) &= SGF(x_4, C, D) = SGF(x_6, C, D) = SGF(x_7, C, D) = SGF(x_8, C, D) \\ &= 2/4 - 0/4 = 0.5 \end{aligned}$$

(3) Determine the weights of each indicator under relevant primary indicator.

According the importance of each indicator, the weights of each indicator can be determined by Equation (7), i.e.,

$$w_i = k_i / \sum_{i=1}^{n} k_i \tag{7}$$

From the result of step 2, we can use Equation (7) to obtain the weights of the 13 tertiary indicators under the primary indicators as follow:

$$w_1(1) = w_3(1) = w_4(1) = w_6(1) = w_7(1) = w_8(1) = 0.1053$$

$$w_2(1) = w_5(1) = w_9(1) = w_{10}(1) = w_{11}(1) = w_{12}(1) = w_{13}(1) = 0.0526$$

(4) Determine the weight value of each primary indicator

Based on the weight of each indicator in its respective category and the real value information standardized, the weight value of primary indicator "innovation resource" can be obtained by weighting sum using Equation (8), i.e.,

$$z_i^1 = \sum_{j=1}^{13} w_j y_{ij} \tag{8}$$

$$z_{\mathrm{bj}}^{1}=\sum_{j=1}^{13}w_{j}y_{\mathrm{bj}j}=0.1053\times(0.69+0.56+0.43+0.65+0.52+0.57)+$$

$$0.0526\times(0.63+0.68+0.24+0.57+0.45+0.73+0.78)=0.5759$$

By the same token, can be obtained as: $z_{\mathrm{sh}}^{1}=0.5046$, $z_{\mathrm{sz}}^{1}=0.3326$, $z_{\mathrm{gz}}^{1}=0.4216$

2) Similarly, the weight and the weight value of primary indicator "innovation input" can be determined:

$$w_{2.1}(2)=w_{2.2}(2)=w_{2.4}(2)=w_{2.5}(2)=0.1429$$

$$w_{2.3}(2)=w_{2.6}(2)=0.2143$$

$$z_{\mathrm{bj}}^{2}=0.6101,\ z_{\mathrm{sh}}^{2}=0.4967,\ z_{\mathrm{sz}}^{2}=0.4330,\ z_{\mathrm{gz}}^{2}=0.2437.$$

3) The weight and the weight value of primary indicator "innovation culture" can be determined:

$$w_{41}(3)=0.4$$

$$w_{43}(3)=w_{44}(3)=w_{45}(3)=0.2$$

$$w_{42}(3)=w_{46}(3)=0$$

$$z_{\mathrm{bj}}^{3}=0.2434,\ z_{\mathrm{sh}}^{3}=0.2138,\ z_{\mathrm{sz}}^{3}=0.7591,\ z_{\mathrm{gz}}^{3}=0.3201.$$

4) The weight and the weight value of primary indicator "innovation platform" can be determined:

$$w_{47}(4)=w_{48}(4)=w_{50}(4)=w_{52}(4)=0.15$$

$$w_{49}(4)=w_{51}(4)=0.2$$

$$z_{\mathrm{bj}}^{4}=0.4283,\ z_{\mathrm{sh}}^{4}=0.4440,\ z_{\mathrm{sz}}^{4}=0.3762,\ z_{\mathrm{gz}}^{4}=0.4831.$$

5) The weight and the weight value of primary indicator "innovation entrepreneurship" can be determined:

$$w_{53}(5)=w_{54}(5)=w_{59}(5)=w_{60}(5)=0.1$$

$$w_{55}(5)=w_{56}(5)=w_{57}(5)=w_{58}(5)=0.15$$

$$z_{\mathrm{bj}}^{5}=0.6171,\ z_{\mathrm{sh}}^{5}=0.3665,\ z_{\mathrm{sz}}^{5}=0.4276,\ z_{\mathrm{gz}}^{5}=0.2346.$$

6) The weight and the weight value of primary indicator "innovation industry" can be determined:

$$w_{61}(6)=w_{63}(6)=0.3$$

$$w_{62}(6)=0.4$$

$$z_{\mathrm{bj}}^{6}=0.5277,\ z_{\mathrm{sh}}^{6}=0.4561,\ z_{\mathrm{sz}}^{6}=0.5864,\ z_{\mathrm{gz}}^{6}=0.3510.$$

7) The weight and the weight value of primary indicator "innovation achievement" can be determined:

$$w_{7.1}(7) = w_{7.2}(7) = w_{7.3}(7) = w_{7.4}(7) = 0.25$$

$$z_{\mathrm{bj}}^{7} = 0.6220,\ z_{\mathrm{sh}}^{7} = 0.3519,\ z_{\mathrm{sz}}^{7} = 0.4397,\ z_{\mathrm{gz}}^{7} = 0.2770.$$

8) The weight and the weight value of primary indicator “innovation impact” can be determined:

$$w_{82}(8) = w_{83}(8) = 0.2143$$

$$w_{84}(8) = w_{85}(8) = w_{86}(8) = w_{87}(8) = 0.1429$$

$$z_{\mathrm{bj}}^{8} = 0.2763,\ z_{\mathrm{sh}}^{8} = 0.3397,\ z_{\mathrm{sz}}^{8} = 0.4462,\ z_{\mathrm{gz}}^{8} = 0.5575.$$

9) the final weight of the whole indicator system can be determined

Selecting the intercept set value $0.9800 \le \lambda$, the weight of 8 primary indicators in the whole indicator system can be determined as follow:

$$w_{c_1} = w_{c_2} = w_{c_4} = w_{c_5} = w_{c_6} = w_{c_7} = w_{c_8} = 0.1111$$

$$w_{c_3} = 0.2222$$

In summary, the weight of each indicator in the Sci-tech Innovation Centers evaluation indicator system can be assigned as shown in Appendix **Table A2**.

4. Results and discussion

4.1. The comprehensive evaluation ranking of Sci-tech Innovation Center is Shenzhen, Beijing, Shanghai and Guangzhou

According to the weight w_j of each indicator in the evaluation indicator system of Sci-tech Innovation Center constructed above and the standardized real value information y_{ij}, the Equation (9) is used to calculate the comprehensive evaluation score Z_i for the four cities of Beijing, Shanghai, Shenzhen and Guangzhou through weighted summing method. (Note: among them, the 51st indicator “emissions of air pollutants per unit of GDP”, the 52nd indicator “energy consumptions per unit of GDP”, the 85th indicator “Urban Sustainability Competitiveness Index ranking “, the 86th indicator “City Business Ability Competitiveness Index ranking”, and the 87th indicator “City livability competitiveness Index ranking” are reverse indicators. The smaller the value, the better the evaluation. Therefore, the weight is calculated with a “-” sign)

$$Z_i = \sum_{j=1}^{87} w_j y_{ij} \tag{9}$$

Get: $Z_{\mathrm{sz}} = 0.4444$, $Z_{\mathrm{bj}} = 0.3996$, $Z_{\mathrm{sh}} = 0.2746$, $Z_{\mathrm{gz}} = 0.2628$.

Based on this Sci-tech Innovation Center evaluation indicator system, the comprehensive evaluation of the four cities is ranked as Shenzhen, Beijing, Shanghai and Guangzhou.

The ranking of these four cities is quite different from previous research rankings by scholars or institutions. Deng Danqing’s ranking order in 2019 was Beijing, Shanghai, Guangzhou, and Shenzhen. The Shanghai Information Center released the ranking order for 2021 as Beijing, Shanghai, Shenzhen, Hong Kong, and Guangzhou, as well as the 2020 ranking order jointly released by Springer Nature and Tsinghua University as Beijing, Shanghai, Hong Kong, and Shenzhen. Guangzhou was not included this time.

In addition to differences in indicator selection orientation, differences in evaluation rankings may also be due to the choice of data processing methods, especially differences in weight setting methods, which will result in significant differences in rankings.

The domestic statistical data collected in this article contains the characteristics of fuzzy, incomplete, and uncertain information. We choose to construct an evaluation index system for science and technology innovation centers based on fuzzy rough set theory, in order to obtain more objective and reasonable evaluation results through "letting the data speak for itself". From the perspective of international technological competition, Shenzhen has a group of high-tech enterprises such as Huawei, ZTE, BYD, DJI, and BGI, which are indeed more in line with the international technological competition situation in terms of ranking.

4.2. DUI mode in Shenzhen has achieved remarkable results

In the comprehensive evaluation above, Shenzhen has formed advantages in three primary indicators, such as "innovational culture" "innovational platform" "innovational industry", and twelve secondary indicators, such as "innovational ecological environment" "patent achievement" "innovational industry achievement" "global influence". The formation of these advantages related to industry verifies the effectiveness of the path of Shenzhen's government DUI.

It is well-known that Shenzhen faced a very shortage of Sci-tech resource at her early stage of development. As the first special zone to open up in China, Shenzhen chose the path of DUI that it firstly in China promoted market-based allocation of economic resource, reformed the institutional mechanism restrained the labor force to promote the free flow of talents, subsidized largely enterprise's R&D, created a culture atmosphere that encourages innovation and entrepreneurship. It aimed to promote entrepreneurs to start their business based on the production of low-end product, follow by introducing new technologies to improve and innovate the product according to the market demand, and then established R&D institution to strengthen the R&D capability to produce high-end product, and when the high-end product stood stably in the domestic market, it has expanded to the international market. At last, the city's high-tech industrial advantage has formed when most enterprises could take part in producing high-end product.

With the help of technological innovation, Shenzhen high-tech enterprises have been deeply integrated into the international industrial ecology system. For example, Companies such as Huawei, DJI and BYD have developed into world-renowned brands in less than 30 years, consolidating the international position of these enterprises in the high-tech supply chain and strengthening the global influence of Shenzhen's scientific and technological innovation. In the 2020 year, the number of PCT international patent application (mainly applied by enterprise) of Shenzhen accounted for 30.19% of the country, it is second only to Tokyo Japan, and significantly ahead of Silicon Valley and New York US internationally, it is 2.44 times higher than Beijing, 5.68 times higher than Shanghai and 11.32 times higher than Guangzhou in China.

The experience of Shenzhen is shows that the focus of the government DUI innovation is the entrepreneurial group, and the main measures to drive this group can be: promoting the market allocation of resources such as labor, land and capital, shaping the culture of innovation and entrepreneurship to cultivate entrepreneurs, building Sci-tech industrial parks to gather entrepreneurship, and most importantly, through subsidies and incentives informing entrepreneurs that Sci-tech can empower them. Those cities or regions with a shortage of innovation resources can learn from Shenzhen's early development experience that use entrepreneurs as a key link to drive sci-tech innovation, in other words that the government drives the entrepreneur's group and accelerates sci-tech innovation by integrating innovation resource inside and outside the region through entrepreneurs.

4.3. STI mode in Beijing has achieved significant results

In the comprehensive evaluation above, Beijing has formed advantages in three primary indicators, such as "innovation resources" "innovation input" "innovation achievement", and ten secondary indicators, such as "business incubation" "entrepreneurial returns" "dissertation achievement" "national influence" "financial capital investment". The formation of these advantages related to transfer and transformation of scientific research achievements verifies the effectiveness of the path of Beijing's government STI innovation.

As the center of administrative power and Sci-tech resources in China, Beijing has built a number of large scientific devices and state key laboratories, (for example, 116 state key laboratories in Beijing, nearly three times as many as Shanghai, six times as many as Guangzhou, twenty times as many as Shenzhen.), and accumulated rich other innovation resources (for example, only Zhongguancun region in Beijing has more than 90 universities and 400 more research institutions, and the number of major national Sci-tech projects undertaken each year accounts for more than one-third of the country.).

Based on the rich innovation resources, Beijing has put the emphasis on STI innovation. In the 1980s, Beijing took Zhongguancun as the starting point to build a large number of incubation platforms for Sci-tech achievements, and introduced venture capital to drive the existing basic research achievements to develop into product models through experiments, and then through small-scale pilot production, and finally industrialization. As we know, the first private technology company in Zhongguancun has been founded by Chen Chunxian who came out from the Institute of Physics of CAS, followed by Lenovo Group, Jinghai Computer Room Technology Development Company, Kehai New Technology Development Center, Beijing Mengzhimo Technology Co. which founded by scientist. However, compared to the huge amount of scientific research results (for example, from 2009 to 2018, the cumulative number of SCI papers published in ten years is 619,047, 308,889, 166,161and 47,763 in Beijing, Shanghai, Guangzhou and Shenzhen respectively), not many scientists could complete the "thrilling jump" from product to commodity. The number of scientific research achievement transformed into industrial results in

Beijing is still relatively low, and the amount of PCT patents applied by enterprises is also low, so Beijing is at a disadvantage in the secondary indicators of "innovative industrial achievement" and "global influence" in this evaluation. At the same time, the evaluation has found that Beijing's R&D results were more transferred than transformed, and its superiority in the number of R&D results has promoted the trading of R&D results in domestic market and increased Beijing's national influence in sci-tech innovation. The convenience of the R&D results trading promotes the full realization of the value of R&D results, and motivate the researcher to put in more innovation resources, then Beijing's source innovation advantage would be strengthened.

The experience of Beijing is shows that the focus of the government STI innovation is the scientist group, and the main measures to drive this group can be: building research platform such as large scientific devices, key laboratories, universities and business incubator (the platform to train scientists into entrepreneurs) for scientist, building trading platform of Sci-tech achievements, investing abundant research funds and attracting high-end talents from the world, and most importantly develop laws and tax breaks that incentivize scientists to actively participate in the transformation of their achievement. Cities or region rich in innovation resource can learn from Beijing's experience and make it a priority for government to help scientists translate their achievement.

5. Policy recommendations

5.1. Unite the four cities to create a national strategic force of Sci-tech

In this comprehensive evaluation, it is found that the four cities have strong complementarity in Sci-tech innovation, especially Beijing's STI and Shenzhen's DUI have a strong and sustainable development trend. Here, we combine with the development goals set by the Chinese government. On 12 March 2021, the "The 14th Five-Year Plan for National Economic and Social Development of the People's Republic of China and the Outline of the Long-range Goals to 2035" was officially released. The plan points out that the strategic needs of the country as the guide to promote the optimal combination system, accelerate the construction of strategic Sci-tech forces leaded by national laboratories. The four cities in the Beijing, Shanghai, Shenzhen, and Guangzhou, whose total economic volume are in the forefront of China, and have strong ability to invest in sci-tech innovation and are building Huairou Science City, Zhangjiang Science City, Guangming Science City and Nansha Science City respectively, and a large number of major Sci-tech infrastructures have been or will be put into use, could be the foundation of building a national strategic Sci-tech force. So, this paper suggests that the four cities should take market demand as the guide, promote the cooperation between industry, academia and research leaded by the leading Sci-tech enterprises such as COMAC, Huawei and BYD, and accelerate the process of the key technology problem breakthrough in the industrial chain, and jointly enhance the overall effectiveness of the national innovation system.

5.2. Shenzhen focus the construction of R&D achievement pilot-base to strength STI innovation

Shenzhen's policy system to DUI has been basically perfected, and formatted the six "90%"[1] innovation advantage. At present, the main difficulties which Shenzhen face is the leading industries are partly stuck with the key core technology held by foreign countries, and the main way to break out of trouble is to add new path to improve the source innovation capacity.

In recent years, Shenzhen has continued to increase investment in basic research to STI, e.g., from 2013 to 2018 years, the average annual growth rate of the number of SCI papers published in Shenzhen is 27.6%, much higher than Beijing's 8.9% and Shanghai's 8.2%. However, it takes time for STI to produce results. In the short term, it is still necessary to leverage domestic and foreign innovation resources and promote the domestic and foreign innovation results being transformed in Shenzhen. Pilot-test-base is a key link in the transformation of R&D results, Shenzhen should increase the investment in the construction of pilot-test-base and make measures to support the construction of pilot-test-base, integrated management of social pilot-test resources, improve the mechanism of benefit distribution, encourage enterprises to participate in the construction of pilot-test-base, in order to attract domestic and foreign research results to transform in Shenzhen.

5.3. Beijing should focus on improving the quality of patents and its conversion rate in STI

Beijing has been rapid growth in patent application since 2012, reaching 241,304 in 2018, an increase of 95.6% in six years, topping the four Cities in terms of growth rate and total volume. This change was probably related to the government's patent incentive policy driving, which was introduced in various districts in Beijing around 2010, such as the "Chaoyang District Patent Funding and Incentive measures" issued by Chaoyang District of Beijing in June 2010. On the other hand, after the comprehensive evaluation in this paper, it is found in Beijing that: the number of industrial enterprises above designated size is lower; the percentage of R&D personnel in enterprises is lower; the output value of high-tech products and exports are lower and the total amount of exports is smaller, etc. Obviously, the advantage of the number of patents has not been transformed into the advantage of Sci-tech industry, which indicates that there are not many high-quality patents, or the enterprises invest less in technological innovation and have difficulty in absorbing and transforming these patented technologies. Suggestion: First, government policy rewards should shift from the quantity target of patents to the quality target, and reward patents according to their transformed market value. Second, more preferential policies should be formulated to support enterprise's R&D, support enterprises to make full use of Beijing's rich innovation resources, strengthen cooperation between industry, university and research institutes, and improve their ability to absorb patent. Third, financial subsidies and tax preferences should be given to enterprises' R&D institutions, guide the flow of scientific and technological personnel to enterprise, and provide enterprise Sci-tech personnel supportation on house and education of their children. Fourth, support enterprise to declare PCT international patents, integrate into the international ecological chain of high technology, and promote their products to the global market.

5.4. Shanghai should focus on the ripening stage of Sci-tech achievement transformation in STI

Shanghai is second only to Beijing in terms of the availability of STI resources in China. As the most complete industrial system in China, Shanghai has a high number of large state-owned manufacturing enterprises. Large enterprises have a higher tolerance for the risks and costs of transforming technological innovation, can create a greater number of new products. But in the comprehensive evaluation of this paper, Shanghai's new product sales growth is found to be slower. At the same time, Shanghai is disadvantaged in the following aspects: knowledge sharing facility penetration rate, enterprise innovation platform, technology business incubation park, energy consumption per unit of GDP and patent achievement per capita, which indicates that Shanghai's insufficient investment in the maturation stage of Sci-tech achievements transformation leads to the lack of attractiveness of Sci-tech achievements to enterprises. Suggestions: First, increase the support on Sci-tech personnel of maturing achievements, e.g., build shared processing platforms to help Sci-tech personnel productize Sci-tech achievements at lower cost. Second, support the development of Sci-tech business incubation parks and vigorously develop the entrepreneurial service industry to provide a better environment for entrepreneurs. Third, support the development of intermediary services for the transformation of Sci-tech achievement, and cultivate a large number of technology broker who can promote Sci-tech achievements to enterprises.

5.5. Guangzhou should focus on promoting financial support for Sci-tech enterprises in DUI

Guangzhou, which has been being at the same frontier of opening up with Shenzhen since 1978, has the market economic cultural advantage of DUI, and has many universities and research institutions, while high-tech industries and high-tech achievements are the weakest among the four cities. In the comprehensive evaluation of this paper, it is found that: less investment in STI and less Tech-Finance resources have led to fewer enterprises with strong STI capability, and less foreign investment in Sci-tech service industry. Therefore, Guangzhou should promote financial support for Sci-tech enterprises as the focus of DUI. Suggestion: first, increase investment in scientific research, especially increase investment in supporting enterprise R&D. Second, increase financial support for Sci-tech, especially increase financial support for industries, universities and research institutes cooperation to help enterprises obtain Sci-tech resources from universities and research institutions. Third, encourage foreign investment in Guangzhou's Sci-tech service industry to optimize the sci-tech ecological environment. Fourth, support the development and promotion of the various types of Sci-tech insurance to help enterprises and individuals to diversify the risk of innovation, and encourage business owners to take the risk of innovation.

6. Conclusion

With the help of sci-tech innovation evaluation indicator system, this paper applies fuzzy rough set method to comprehensively evaluate the effectiveness of the two paths based on public statistics data of four first-tier cities in Beijing, Shanghai, Guangzhou and Shenzhen.

This paper finds that: first, DUI is significantly effective in Shenzhen. Second, STI is significantly effective in Beijing. Third, when the accumulated innovation resources of a city reach a certain level, adjustments should be made on the path, for example, Shenzhen should shift its focus on the path of STI from the path of DUI. Forth, STI or DUI, the government policies and work priorities are different with different paths chosen. The conclusions of this paper are based on the comparative analysis of the four cities and do not address specific policies, which can be followed up with targeted research on the specific innovation policies of each city.

The limitation of this study is that the evaluation index system of technology innovation centers may need to be dynamically adjusted with the development of technology and the market in order to adapt to new trends in technology innovation. Suggestions for future research: With the rapid development of technology, regularly update data and evaluation indicator systems to reflect the latest trends in technological innovation and market changes. Consider introducing more quantitative and qualitative research methods, such as case studies, in-depth interviews, etc., to enhance the depth and breadth of the research.

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Notes

[1] More than 90% of innovative enterprises are local enterprises, more than 90% of city's R&D institutions are set up in enterprises, more than 90% of city's R&D personnel are concentrated in enterprises, more than 90% of city's R&D funds come from enterprises, more than 90% of city's vocational invention patents come from enterprises, and more than 90% of city's invention patents of major science and technology project come from leading enterprises.

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Appendix

Table A1. Evaluation index system of Sci-tech Innovation Center and its real value information standardization table.

First order	Tier 1 indicator	Second order	Secondary indicator	Three Sequences	Tier 3 indicator	Beijing	Shanghai	Shenzhen	Guangzhou
1	Innovation resources	1.1	Talent resources	1.1.1	Number of employees in the financial industry	0.69	0.60	0.34	0.21
1	Innovation resources	1.1	Talent resources	1.1.2	Number of financial employees per 10,000 people.	0.63	0.50	0.52	0.28
1	Innovation resources	1.1	Talent resources	1.1.3	Number of full-time teachers in general higher education schools per million people	0.56	0.33	0.09	0.75
1	Innovation resources	1.1	Talent resources	1.1.4	Number of students enrolled in general higher education schools	0.43	0.39	0.08	0.81
1	Innovation resources	1.1	Talent resources	1.1.5	Number of people employed in higher education in urban per million people	0.68	0.33	0.09	0.65
1	Innovation resources	1.1	Talent resources	1.1.6	Number of returnees from Study abroad in high and new technology enterprises	0.65	0.69	0.32	0.07
1	Innovation resources	1.2	Technical resources	1.2.1	Per capita of fixed asset investment in scientific research and technology services	0.52	0.59	0.48	0.38
1	Innovation resources	1.2	Technical resources	1.2.2	Number of fixed asset investment in Scientific research and technology services industry	0.57	0.65	0.45	0.22
1	Innovation resources	1.2	Technical resources	1.2.3	Number of industrial enterprises above designated size with R&D activities	0.24	0.47	0.75	0.40
1	Innovation resources	1.3	Capital resources	1.3.1	Economic growth rate	0.57	0.46	0.53	0.43
1	Innovation resources	1.3	Capital resources	1.3.2	Gross Domestic Product per capita	0.45	0.43	0.61	0.50
1	Innovation resources	1.3	Capital resources	1.3.3	The Proportion of the Value added of scientific research and technology services in GDP	0.73	0.49	0.21	0.43
1	Innovation resources	1.3	Capital resources	1.3.4	The target size of the government entrepreneurial guidance fund	0.78	0.43	0.07	0.45
2	Innovation input	2.1	Human capital input	2.1.1	Number of R&D personnel per 10,000 people	0.50	0.31	0.72	0.37
2	Innovation input	2.1	Human capital input	2.1.2	The proportion of various types of professional and technical personnel in the permanent population	0.69	0.59	0.31	0.28
2	Innovation input	2.1	Human capital input	2.1.3	The proportion of R&D personnel in industrial enterprises above designated size employed personnel	0.18	0.28	0.88	0.34

Table A1. (*Continued*).

First order	Tier 1 indicator	Second order	Secondary indicator	Three Sequences	Tier 3 indicator	Beijing	Shanghai	Shenzhen	Guangzhou
2	Innovation input	2.1	Human capital input	2.1.4	Full-time equivalent of R&D personnel in high-tech enterprises	0.43	0.35	0.77	0.31
2	Innovation input	2.2	Technology capital investment	2.2.1	Full-time equivalent of R&D personnel	0.58	0.41	0.65	0.29
2	Innovation input	2.2	Technology capital investment	2.2.2	The proportion of R&D expenditure in GDP	0.67	0.45	0.52	0.28
2	Innovation input	2.2	Technology capital investment	2.2.3	The proportion of Regional R&D expenditure in national expenditure	0.70	0.51	0.44	0.23
2	Innovation input	2.2	Technology capital investment	2.2.4	The proportion of R&D expenditure in the main business income of industrial enterprises above designated size	0.34	0.38	0.77	0.39
2	Innovation input	2.3	Financial capital investment	2.3.1	The cumulative number of unicorn enterprises	0.80	0.54	0.26	0.04
2	Innovation input	2.3	Financial capital investment	2.3.2	Number of companies receiving investment in seed, start-up and expansion stages	0.80	0.51	0.27	0.12
2	Innovation input	2.3	Financial capital investment	2.3.3	The sum money of investment received in seed, start-up and expansion stages of companies	0.77	0.61	0.15	0.13
2	Innovation input	2.4	Government input	2.4.1	The proportion of the industrial enterprises with R&D activities above designated size in the total number of enterprises	0.48	0.36	0.60	0.53
2	Innovation input	2.4	Government input	2.4.2	The proportion of investment in Sci-tech in general public budget expenditure	0.35	0.31	0.79	0.40
2	Innovation input	2.4	Government input	2.4.3	Number of libraries per 100 million people	0.02	0.02	1.00	0.02
2	Innovation input	2.4	Government input	2.4.4	Per capita expenditure on Sci-tech in the general public budget	0.51	0.51	0.66	0.20
2	Innovation input	2.4	Government input	2.4.5	Per capita expenditure on education in the general public budget	0.59	0.47	0.55	0.36
2	Innovation input	2.4	Government input	2.4.6	Number of government start-up guidance funds	0.48	0.76	0.28	0.34
2	Innovation input	2.4	Government input	2.4.7	Number of industry enterprise above designated size	0.25	0.64	0.62	0.38
2	Innovation input	2.4	Government input	2.4.8	Per capita expenditure on R&D of industry enterprise above designated size	0.53	0.62	0.45	0.37
2	Innovation input	2.5	Industry input	2.5.1	Average annual salary–Finance industry	0.54	0.55	0.54	0.34

Table A1. (*Continued*).

First order	Tier 1 indicator	Second order	Secondary indicator	Three Sequences	Tier 3 indicator	Beijing	Shanghai	Shenzhen	Guangzhou
2	Innovation input	2.5	Industry input	2.5.2	Average annual salary–Scientific research and technical services industry	0.47	0.51	0.55	0.46
2	Innovation input	2.5	Industry input	2.5.3	Average annual salary–Information transmission, software and information technology services industry	0.52	0.51	0.52	0.44
2	Innovation input	2.5	Industry input	2.5.4	The proportion of enterprise funds in social R&D expenditures	0.32	0.45	0.68	0.47
2	Innovation input	2.6	Regional external input	2.6.1	M&A market trade volume	0.77	0.44	0.45	0.12
2	Innovation input	2.6	Regional external input	2.6.2	The amount of foreign direct investment actually used-Scientific research and technical services industry	0.95	0.29	0.07	0.08
2	Innovation input	2.6	Regional external input	2.6.3	The amount of foreign direct investment actually used-Information transmission, software and information technology services industry	0.89	0.44	0.08	0.06
2	Innovation input	2.6	Regional external input	2.6.4	The amount of foreign direct investment actually used-Finance industry	0.36	0.87	0.31	0.11
3	Innovation culture	3.1	Knowledge Sharing Facility	3.1.1	Number of Public Libraries	0.04	0.04	1.00	0.02
3	Innovation culture	3.1	Knowledge Sharing Facility	3.1.2	Number of hospital beds per 10,000 people	0.56	0.52	0.33	0.56
3	Innovation culture	3.1	Knowledge Sharing Facility	3.1.3	Rate of 5G/4G user penetration	0.43	0.37	0.54	0.62
3	Innovation culture	3.2	Intellectual property protection	3.2.1	Number of IPR infringement cases investigated and dealt with	0.15	0.12	0.63	0.76
3	Innovation culture	3.2	Intellectual property protection	3.2.2	Number of IPR infringement cases closed	0.56	0.51	0.63	0.19
3	Innovation culture	3.2	Intellectual property protection	3.2.3	The proportion of IPR infringement cases closed in the total cases accepted by intellectual property courts	0.51	0.52	0.53	0.44
4	Innovation platform	4.1	Innovation technology platform	4.1.1	Number of industry enterprise above designated size per 10000 people	0.19	0.43	0.78	0.41
4	Innovation platform	4.1	Innovation technology platform	4.1.2	Number of municipal and above enterprise technology centers	0.45	0.21	0.52	0.69
4	Innovation platform	4.2	Innovation entrepreneurship platform	4.2.1	The proportion of total amount of regional venture capital in the country	0.94	0.26	0.20	0.04
4	Innovation platform	4.2	Innovation entrepreneurship platform	4.2.2	Number of incubation park of Sci-tech enterprise per million people	0.25	0.26	0.51	0.78

Table A1. (*Continued*).

First order	Tier 1 indicator	Second order	Secondary indicator	Three Sequences	Tier 3 indicator	Beijing	Shanghai	Shenzhen	Guangzhou
4	Innovation platform	4.3	Innovative ecological environment	4.3.1	Emissions of air pollutants per unit of GDP	0.20	0.78	0.06	0.58
4	Innovation platform	4.3	Innovative ecological environment	4.3.2	Energy consumptions per unit of GDP	0.45	0.66	0.34	0.50
5	Innovative entrepreneur ship	5.1	Business incubation	5.1.1	Number of incubating enterprises in technology business incubator	0.60	0.54	0.40	0.44
5	Innovative entrepreneur ship	5.1	Business incubation	5.1.2	Number of technology business incubator	0.34	0.40	0.43	0.74
5	Innovative entrepreneur ship	5.1	Business incubation	5.1.3	Total incubation fund for technology enterprises	0.86	0.45	0.13	0.20
5	Innovative entrepreneur ship	5.2	Entrepreneurship input	5.2.1	Number of venture capital firms (early-stage invest firms +VC+PE)	0.81	0.41	0.35	0.23
5	Innovative entrepreneur ship	5.2	Entrepreneurship input	5.2.2	Annual increase Number of enterprises listed on the GEM	0.02	0.00	1.00	0.01
5	Innovative entrepreneur ship	5.3	Entrepreneurial returns	5.3.1	Return amount of exited angel investment and venture capital	0.93	0.33	0.16	0.02
5	Innovative entrepreneur ship	5.3	Entrepreneurial returns	5.3.2	IRR of exited angel investment and venture capital	0.53	0.42	0.63	0.37
5	Innovative entrepreneur ship	5.3	Entrepreneurial returns	5.3.3	Number of exited angel investment and venture capital	0.78	0.52	0.34	0.10
6	Innovation Industry	6.1	knowledge intensive business service	6.1.1	The proportion of the value added of the financial sector in GDP	0.58	0.61	0.44	0.31
6	Innovation Industry	6.2	High-tech manufactured goods industry	6.2.1	The added value of strategic emerging industries	0.39	0.44	0.74	0.33
6	Innovation Industry	6.2	High-tech manufactured goods industry	6.2.2	Number of new and high-tech enterprises in statistical system	0.68	0.33	0.51	0.42
7	Innovation achievement s	7.1	Dissertation achievements	7.1.1	Number of SCI papers published	0.86	0.42	0.11	0.26
7	Innovation achievement s	7.2	Patent Achievements	7.2.1	The proportion of PCT international patent applications number in the country	0.33	0.13	0.93	0.13
7	Innovation achievement s	7.2	Patent Achievements	7.2.2	The proportion of invent patent granted number in the country	0.83	0.38	0.37	0.19
7	Innovation achievement s	7.2	Patent Achievements	7.2.3	The number of invent patent granted per 10,000 people	0.74	0.30	0.55	0.25

Table A1. (*Continued*).

First order	Tier 1 indicator	Second order	Secondary indicator	Three Sequences	Tier 3 indicator	Beijing	Shanghai	Shenzhen	Guangzhou
7	Innovation achievement s	7.2	Patent Achievements	7.2.4	The number of domestic patents granted per 10,000 employees	0.48	0.33	0.65	0.49
7	Innovation achievement s	7.2	Patent Achievements	7.2.5	The growth rate of invent patents granted	0.09	0.15	0.62	0.76
7	Innovation achievement s	7.2	Patent Achievements	7.2.6	The total amount of patents granted	0.54	0.41	0.62	0.40
7	Innovation achievement s	7.2	Patent Achievements	7.2.7	The proportion of the total number of regional patents granted in the country	0.54	0.41	0.62	0.40
7	Innovation achievement s	7.3	Innovation trading achievements	7.3.1	The amount of technology output transaction in the technology transaction market	0.96	0.24	0.11	0.14
7	Innovation achievement s	7.3	Innovation trading achievements	7.3.2	The amount of technology input transaction in the technology transaction market	0.86	0.32	0.35	0.17
7	Innovation achievement s	7.3	Innovation trading achievements	7.3.3	The proportion of the amount of regional technology input transaction in the national technology transaction market	0.86	0.32	0.35	0.17
7	Innovation achievement s	7.3	Innovation trading achievements	7.3.4	The proportion of the amount of regional technology output transaction in the national technology transaction market	0.96	0.24	0.11	0.14
7	Innovation achievement s	7.3	Innovation trading achievements	7.3.5	The number of technology output transaction contracts in the technology transaction market	0.95	0.25	0.11	0.14
7	Innovation achievement s	7.4	Innovation industry achievements	7.4.1	Total industrial output value of high-tech enterprises	0.27	0.51	0.76	0.30
7	Innovation achievement s	7.4	Innovation industry achievements	7.4.2	The proportion of total industrial output of high-tech enterprises in GDP	0.23	0.40	0.82	0.34
7	Innovation achievement s	7.4	Innovation industry achievements	7.4.3	The proportion of high-tech exports in total exports	0.28	0.58	0.70	0.30
7	Innovation achievement s	7.4	Innovation industry achievements	7.4.4	The export value of high-tech products	0.20	0.44	0.85	0.20
7	Innovation achievement s	7.4	Innovation industry achievements	7.4.5	The proportion of added value of strategic emerging industries in GDP	0.34	0.35	0.79	0.37
8	Innovation impact	8.1	Global influence	8.1.1	Total value of exports	0.22	0.61	0.72	0.25

Table A1. (*Continued*).

First order	Tier 1 indicator	Second order	Secondary indicator	Three Sequences	Tier 3 indicator	Beijing	Shanghai	Shenzhen	Guangzhou
8	Innovation impact	8.2	Regional influence capability	8.2.1	Growth rate of new product sales of industrial enterprises above designated size	0.04	(0.27)	(0.07)	0.96
8	Innovation impact	8.2	Regional influence capability	8.2.2	The proportion of new product sales of industrial enterprises above designated size in total product sales	0.35	0.46	0.66	0.48
8	Innovation impact	8.3	National influence	8.3.1	Urban Sustainability Competitiveness Index ranking	0.27	0.41	0.54	0.68
8	Innovation impact	8.3	National influence	8.3.2	City business ability competitiveness index ranking	0.27	0.41	0.54	0.68
8	Innovation impact	8.3	National influence	8.3.3	City livability competitiveness Index ranking	0.65	0.60	0.40	0.25

Note: Data normalization.

Table A2. Evaluation indicator weights and comprehensive evaluation of Sci-tech Innovation Center.

System serial number	First order	First order weights	Third order	Third order weights	Three sequences	Three sequences weights	BJ three sequences assignment value	SH three sequences assignment value	SZ three sequences assignment value	GZ three sequences assignment value
1	1	0.1111	1.1	0.0585	1.1.1	0.0117	0.0080	0.0071	0.0040	0.0024
2					1.1.2	0.0058	0.0037	0.0029	0.0031	0.0016
3					1.1.3	0.0117	0.0066	0.0039	0.0011	0.0088
4					1.1.4	0.0117	0.0051	0.0045	0.0009	0.0095
5					1.1.5	0.0058	0.0040	0.0019	0.0005	0.0038
6					1.1.6	0.0117	0.0076	0.0080	0.0038	0.0008
7			1.2	0.0292	1.2.1	0.0117	0.0061	0.0069	0.0056	0.0045
8					1.2.2	0.0117	0.0067	0.0076	0.0053	0.0025
9					1.2.3	0.0058	0.0014	0.0027	0.0044	0.0023
10			1.3	0.0234	1.3.1	0.0058	0.0033	0.0027	0.0031	0.0025
11					1.3.2	0.0058	0.0026	0.0025	0.0035	0.0029
12					1.3.3	0.0058	0.0043	0.0029	0.0012	0.0025
13					1.3.4	0.0058	0.0046	0.0025	0.0004	0.0026
14	2	0.1111	2.1	0.0159	2.1.1	0.0043	0.0022	0.0013	0.0031	0.0016
15					2.1.2	0.0043	0.0030	0.0026	0.0013	0.0012
16					2.1.3	0.0043	0.0008	0.0012	0.0038	0.0015
17					2.1.4	0.0029	0.0013	0.0010	0.0022	0.0009
18			2.2	0.0159	2.2.1	0.0032	0.0018	0.0013	0.0020	0.0009
19					2.2.2	0.0048	0.0032	0.0021	0.0025	0.0014
20					2.2.3	0.0048	0.0034	0.0024	0.0021	0.0011
21					2.2.4	0.0032	0.0011	0.0012	0.0024	0.0012

Table A2. (*Continued*).

System serial number	First order	First order weights	Third order	Third order weights	Three sequences	Three sequences weights	BJ three sequences assignment value	SH three sequences assignment value	SZ three sequences assignment value	GZ three sequences assignment value
22			2.3	0.0238	2.3.1	0.0079	0.0064	0.0043	0.0020	0.0003
23					2.3.2	0.0079	0.0064	0.0041	0.0022	0.0009
24					2.3.3	0.0079	0.0061	0.0048	0.0012	0.0011
25			2.4	0.0159	2.4.1	0.0018	0.0008	0.0006	0.0011	0.0009
26					2.4.2	0.0018	0.0006	0.0005	0.0014	0.0007
27					2.4.3	0.0000	0.0000	0.0000	0.0000	0.0000
28					2.4.4	0.0018	0.0009	0.0009	0.0012	0.0003
29					2.4.5	0.0026	0.0016	0.0012	0.0015	0.0010
30					2.4.6	0.0026	0.0013	0.0020	0.0007	0.0009
31					2.4.7	0.0026	0.0007	0.0017	0.0016	0.0010
32					2.4.8	0.0026	0.0014	0.0016	0.0012	0.0010
33			2.5	0.0159	2.5.1	0.0040	0.0021	0.0022	0.0021	0.0014
34					2.5.2	0.0040	0.0019	0.0020	0.0022	0.0018
35					2.5.3	0.0040	0.0021	0.0020	0.0021	0.0017
36					2.5.4	0.0040	0.0013	0.0018	0.0027	0.0019
37			2.6	0.0238	2.6.1	0.0060	0.0046	0.0026	0.0027	0.0007
38					2.6.2	0.0060	0.0057	0.0017	0.0004	0.0005
39					2.6.3	0.0060	0.0053	0.0026	0.0005	0.0004
40					2.6.4	0.0060	0.0022	0.0052	0.0018	0.0007
41	3	0.2222	3.1	0.1333	3.1.1	0.0889	0.0033	0.0031	0.0887	0.0019
42					3.1.2	0.0000	0.0000	0.0000	0.0000	0.0000
43					3.1.3	0.0444	0.0193	0.0166	0.0240	0.0274
44			3.2	0.0889	3.2.1	0.0444	0.0068	0.0053	0.0278	0.0336
45					3.2.2	0.0444	0.0247	0.0225	0.0282	0.0082
46					3.2.3	0.0000	0.0000	0.0000	0.0000	0.0000
47	4	0.1111	4.1	0.0333	4.1.1	0.0167	0.0032	0.0071	0.0130	0.0069
48					4.1.2	0.0167	0.0076	0.0036	0.0086	0.0115
49			4.2	0.0389	4.2.1	0.0222	0.0209	0.0059	0.0045	0.0009
50					4.2.2	0.0167	0.0041	0.0043	0.0086	0.0130
51			4.3	0.0389	4.3.1	0.0222	0.0044	0.0174	0.0014	0.0130
52					4.3.2	0.0167	0.0074	0.0110	0.0057	0.0083
53	5	0.1111	5.1	0.0389	5.1.1	0.0111	0.0066	0.0060	0.0045	0.0048
54					5.1.2	0.0111	0.0037	0.0044	0.0047	0.0082
55					5.1.3	0.0167	0.0143	0.0075	0.0022	0.0034
56			5.2	0.0333	5.2.1	0.0167	0.0135	0.0068	0.0059	0.0038
57					5.2.2	0.0167	0.0004	0.0000	0.0167	0.0002
58			5.3	0.0389	5.3.1	0.0167	0.0155	0.0056	0.0027	0.0004
59					5.3.2	0.0111	0.0059	0.0046	0.0071	0.0041
60					5.3.3	0.0111	0.0086	0.0058	0.0038	0.0011

Table A2. (*Continued*).

System serial number	First order	First order weights	Third order	Third order weights	Three sequences	Three sequences weights	BJ three sequences assignment value	SH three sequences assignment value	SZ three sequences assignment value	GZ three sequences assignment value
61	6	0.1111	6.1	0.0333	6.1.1	0.0333	0.0193	0.0204	0.0146	0.0105
62			6.2	0.0778	6.2.1	0.0444	0.0175	0.0195	0.0328	0.0146
63					6.2.2	0.0333	0.0226	0.0109	0.0170	0.0140
64	7	0.1111	7.1	0.0278	7.1.1	0.0278	0.0240	0.0116	0.0030	0.0074
65			7.2	0.0278	7.2.1	0.0062	0.0021	0.0008	0.0057	0.0008
66					7.2.2	0.0031	0.0025	0.0012	0.0012	0.0006
67					7.2.3	0.0031	0.0023	0.0009	0.0017	0.0008
68					7.2.4	0.0031	0.0015	0.0010	0.0020	0.0015
69					7.2.5	0.0062	0.0006	0.0010	0.0038	0.0047
70					7.2.6	0.0031	0.0017	0.0013	0.0019	0.0012
71					7.2.7	0.0031	0.0017	0.0013	0.0019	0.0012
72			7.3	0.0278	7.3.1	0.0056	0.0053	0.0013	0.0006	0.0008
73					7.3.2	0.0056	0.0048	0.0018	0.0020	0.0009
74					7.3.3	0.0056	0.0048	0.0018	0.0020	0.0009
75					7.3.4	0.0056	0.0053	0.0013	0.0006	0.0008
76					7.3.5	0.0056	0.0053	0.0014	0.0006	0.0008
77			7.4	0.0278	7.4.1	0.0056	0.0015	0.0028	0.0042	0.0017
78					7.4.2	0.0056	0.0013	0.0022	0.0045	0.0019
79					7.4.3	0.0056	0.0016	0.0032	0.0039	0.0016
80					7.4.4	0.0056	0.0011	0.0025	0.0047	0.0011
81					7.4.5	0.0056	0.0019	0.0019	0.0044	0.0021
82	8	0.1111	8.1	0.0238	8.1.1	0.0238	0.0052	0.0145	0.0172	0.0059
83			8.2	0.0397	8.2.1	0.0238	0.0010	(0.0065)	(0.0017)	0.0228
84					8.2.2	0.0159	0.0056	0.0073	0.0105	0.0076
85			8.3	0.0476	8.3.1	0.0159	0.0043	0.0065	0.0086	0.0108
86					8.3.2	0.0159	0.0043	0.0065	0.0086	0.0108
87					8.3.3	0.0159	0.0103	0.0095	0.0063	0.0040
		0.9999		0.9999		0.9999				
Comprehensive evaluation							0.3996	0.2746	0.4444	0.2628