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Regional Economic Efficiency and Its Influencing Factors of Beijing-Tianjin-Hebei Metropolitans in China Based on a Heterogeneity Stochastic Frontier Model

HUANG Xingling[1], LIU Jianguo[2]

(1. *School of Government*, *Peking University*, *Beijing* 100871, *China*; 2.*Tourism College*, *Beijing Union University*, *Beijing* 100101, *China*)

Abstract: Using a heterogeneity stochastic frontier model (HSFM), we empirically investigated the economic efficiency of Beijing-Tianjin-Hebei from 2003 to 2016 and its influencing factors. The key findings of the paper lie in: 1) in Beijing-Tianjin-Hebei, the overall economic and technological efficiency tended to increase in a wavelike manner, economic growth slowed down, and there was an obvious imbalance in economic efficiency between the different districts, counties and cities; 2) the heterogeneity stochastic frontier production functions (SFPFs) of Beijing, Tianjin and Hebei were different from each other, and investment was still an important impetus of economic growth in Beijing-Tianjin-Hebei; 3) economic efficiency was positively correlated with economic agglomeration, human capital, industrial structure, infrastructure, the informatization level, and institutional factors, but negatively correlated with the government role and economic opening. The following policy suggestions are offered: 1) to improve regional economic efficiency and reduce the economic gap in Beijing-Tianjin-Hebei, governments must reduce their intervention in economic activities, stimulate the potentials of labor and capital, optimize the structure of human resources, and foster new demographic incentives; 2) governments must guide economic factors that are reasonable throughout Beijing-Tianjin-Hebei and strengthen infrastructure construction in underdeveloped regions, thus attaining sustainable economic development; 3) governments must plan overall economic growth factors of Beijing-Tianjin-Hebei and promote reasonable economic factors (e.g., labor, resources, and innovations) across different regions, thus attaining complementary advantages between Beijing, Tianjin, and Hebei.

Keywords: economy efficiency; total factor productivity (TFP); Beijing-Tianjin-Hebei; heterogeneity stochastic frontier model

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1 Introduction

Over the 40 years after the reform and opening-up, China's economy has attained world-renowned achievements, turning China into the second largest economy worldwide. By the end of 2018, China's urbanization rate was approximately 60%. Along with rapid economic growth and increasing urbanization rate, China is confronted with problems, such as haphazard investment and overinvestment in certain sectors, when governments pursue economic aggregates. As a result, resources are rapidly concentrated on a few sectors, resulting in misallocation of regional resources and economic inefficiency. This affects not only regional indus-

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Corresponding author: LIU Jianguo. E-mail: liujianguo009@163.com

trial restructuring, but also sustainable development of the regional economy. As China's economy has entered the medium and high-speed growth stage, a popular issue in academia is how to ensure high-efficiency and high-quality regional economic growth and address the imbalance of regional economic development.

Regional economic efficiency refers to the economic benefits that are produced in a region subsequent to the input of a certain amount of resource factors. It is usually used to evaluate the quality of economic development in a country or region. After the Cobb-Douglas (C-D) production function was proposed in the early 20th century, productivity has been widely studied in academia. Studying the growth of economic output, Abramovitz (1956) found that economic growth is promoted by not only production factors but also non-production factors. Solow (1956) ascribed this to technological progress, also known as the Solow residual (or total factor productivity (TFP)). Subsequently, in-depth studies were conducted worldwide with respect to economic efficiency and TFP, resulting in a number of findings with theoretical and practical value. Researchers mainly investigated TFP and its contribution to economic growth on different spatial and temporal scales. From a macro-regional perspective, studies show that regional TFP has spatial differences (Liu et al., 2012; Otsuka and Goto, 2016; Akihiro, 2017) and that economic efficiency is significantly affected by a variety of factors, including knowledge capital (Cheng and Chen, 2017), technological progress (Diewert and Fox, 2018), economic agglomeration (Ehrl, 2013), urbanization (Kuo et al., 2010), and foreign investment (Kumbhakar, 2017). On the scale of a city cluster and city, studies show that the economic performance of a city increases significantly, the economic efficiency of a city is closely linked with its urban level (Zhao et al., 2016; Huang et al., 2017), technological progress is the main driving force of regional TFP (Bergeaud et al., 2018), and the growth rate of urban TFP follows the sequence: large city > small city > medium-sized city (Han et al., 2017). In terms of measuring method, data envelopment analysis (DEA) and stochastic frontier analysis (SFA) are commonly used methods for measuring economic efficiency, because they consider diverse inputs and outputs and can be used to compare the economic efficiency between many regions (Liu et al., 2012; Tong et al., 2012; Liu and Zhang, 2014; Zhang et al. 2016; Han et al., 2017; Li et al., 2017b; Liu et al., 2017; Diewert and Fox, 2018; Escribá-Pérez and Murgui-García, 2018; Yin and Tan, 2019). Because of its borderlessness and vulnerability, DEA is prone to cause calculation errors and thus can not overcome the inefficiency arising from index variables. SFA can not analyze the influence of exogenous variables on the inefficiency variance, although it can overcome the defects of DEA, calculate the influencing parameter of the technological inefficiency function, and reduce the errors of data calculation. Therefore, scholars introduced the HSFM method to study the efficiency issue. The HSFM method can overcome the defects of DEA and SFA, analyze the influence of exogenous variables on the inefficiency equation, and calculate the technological efficiency of each specific variable under the influence of exogenous variables.

Based on existing studies, we measured the regional economic efficiency of Beijing-Tianjin-Hebei from 2003 to 2016 and investigated the sources and influencing factors of economic efficiency growth. This study provides the following innovations: 1) from the perspective of TFP, the technological heterogeneity of regional economic efficiency is introduced into the stochastic frontier model to construct heterogeneity stochastic frontier production functions (SFPFs) for Beijing, Tianjin and Hebei, thus determining the structural differences of frontier technologies between Beijing, Tianjin and Hebei; 2) the influencing factors of the regional economic efficiency in Beijing-Tianjin-Hebei are decomposed to discuss the heterogeneity between factors from multiple perspectives.

2 Materials and Methods

2.1 Heterogeneity stochastic frontier model (HSFM)

Using the stochastic frontier analysis (SFA) methods for reference (Aigner et al., 1977; Meeusen and van den Broeck, 1977), errors were classified into random errors and technological inefficiency errors. Specifically, random errors refer to the errors that arise from uncontrollable or unobservable factors, and technological inefficiency errors refer to the errors that arise from non-technological factors.

In a SFA model, assume that technological efficiency is enough. Then, set the maximum actual output of the district, country, or city i, in year t as Y_{it}, which is the output frontier. A region's economic development primarily depends on diverse decision variables. Here, set the input of the i decision variables during the time period t to X_{it}. In practice, unpredictable and random factors usually hamper economic development. Therefore, such random influencing factors are categorized under the error term v_{it}; moreover, assume $v_{it} \sim N(0, \sigma_v^2)$, namely, it obeys a normal distribution. Then, the optimal output of a district, county, or city (Y_{it}^*) can be denoted as follows:

$$Y_{it}^* = f(X_{it}, \beta) + v_{it} \tag{1}$$

where $i = 1, 2, 3,\ldots, N$, and $t = 1, 2, 3, \ldots,T$. In practice, inefficiency factors usually hamper economic development and cause the regional economy to generate the inefficiency part. As a result, the actual output can not reach the optimal output Y_{it}^*. Therefore, the radial distance between the actual output Y_{it}, and the optimal output Y_{it}^*, is defined as the efficiency loss. Its error term comprises the random disturbance term v_{it}, and the unilaterally distributed inefficiency error term u_{it}. $v_{it}-u_{it}$ is the composite error structure. Then, the radial distance between the actual output and optimal output on the frontier is defined as the efficiency loss, $Q(Z_{it})$, which can be expressed as follows:

$$Q(Z_{it}) = Y_{it}^* - Y_{it} \tag{2}$$

where $Q(Z_{it}) = u_{it} \geq 0$. Assume that $f(X_{it})$ obeys a linear function. Then, the actual production function of the economic efficiency in the Beijing-Tianjin-Hebei region is expressed as follows:

$$Y_{it} = Y_{it}^* - u_{it} = \beta x'_{it} + v_{it} - u_{it} \tag{3}$$

As the inefficiency term of the output, u_{it} is characterized by a unilateral distribution. Therefore, assume that the inefficiency part obeys the non-negative truncated half-normal distribution, namely, $u_{it} \sim N(\omega_{it}, \sigma^2_{it})$. Further, introduce an exogenous variable by applying a heterogeneity setting to u_{it}:

$$\omega_{it} = \exp(b_0 + z'_{it}\delta), \quad \sigma_{it}^2 = \exp(b_1 + z'_{it}\gamma) \tag{4}$$

where b_0 and b_1 are intercept terms, z'_{it} is a variable that affects the regional economic and technological efficiency, and δ and γ are parameters to be estimated. The setting allows the exogenous variable to affect the mean value (ω_{it}) and variance (σ_{it}^2), except that the initial effect and degree of effect are the difference between them. The heterogeneity setting can be used to not only analyze the effect of the exogenous variable on ω_{it} and σ_{it}^2 but also to quantitatively analyze the technological efficiency loss under the conditional constraint.

Further, the maximum likelihood method is used to estimate the HSFM that comprises Equations (3) and (4). Its log-likelihood function is as follows:

$$\ln L = -0.5\ln\left(\sigma_v^2 + \sigma_{it}^2\right) + \ln\left[\phi\left(\varepsilon_{it} + \omega_{it}\right) / \sqrt{\sigma_v^2 + \sigma_{it}^2}\right] - \ln\left[\Phi\left(\omega_{it} / \sigma_{it}\right)\right] + \ln\left[\Phi\left(\tilde{\omega}_{it} / \tilde{\sigma}_{it}\right)\right] \tag{5}$$

where $\tilde{\omega}_{it} = \left(\sigma_v^2\omega_{it} - \sigma_{it}^2\varepsilon_{it}\right) / \left(\sigma_v^2 + \sigma_{it}^2\right)$, $\tilde{\sigma}_{it} = \left(\sigma_v^2\sigma_{it}^2\right) / \left(\sigma_v^2 + \sigma_{it}^2\right)$, and $\phi(\cdot)$ and $\Phi(\cdot)$ are the density function and cumulative distribution function, respectively, that obey the standard normal distribution.

The effect of various constraints on the regional input and output is analyzed in two ways. First, the effect is qualitatively analyzed through a likelihood-ratio test. The original hypothesis is H_0: $u_{it} = 0$ (no efficiency loss), the alternative hypothesis is H_1: $u_{it} \neq 0$, the likelihood ratio statistic is $LR = -2[L(H_0) - L(H_1)]$, and $L(H_0)$ and $L(H_1)$ are the likelihood function values of the original hypothesis and alternative function, respectively. The LR statistic progressively obeys the x distribution, and the degree of freedom is the number of constraint variables. In addition, the likelihood ratio test can also be used for model discrimination. Second, this effect is quantitatively analyzed through the input-output efficiency index, (IEI_{it}). IEI_{it} denotes the degree of deviation of the actual output from optimal output in the districts, counties, or cities of Beijing, Tianjin and Hebei. Specifically, it is expressed as follows:

$$IEI_{it} = \frac{\exp\left(x'_{it}\beta - u_{it}\right)}{\exp\left(x'_{it}\beta\right)} = \exp\left(-u_{it}\right) \tag{6}$$

The IEI_{it} value is in the range of 0 to 1. When IEI_{it} is equal to 0 ($u_{it} \to \infty$), the input-output efficiency is minimized, and the constraints are maximized. When IEI_{it} is equal to 0 (u_{it}→0), the input-output efficiency is maximized, and the constraints are minimized. After the parameter values of the maximum likelihood estimation model are used, the estimation of the input-output efficiency index (IEI_{it}) is determined as follows:

$$IEI_{it} = E\left[\exp\left(-u_{it}\middle|\varepsilon_{it} = \hat{\varepsilon}_{it}\right)\right] = \exp(-\tilde{\omega}_{it} + 0.5\tilde{\sigma}_{it})\frac{\Phi\left(\tilde{\omega}_{it}/\tilde{\sigma}_{it} - \tilde{\sigma}_{it}\right)}{\Phi\left(\tilde{\omega}_{it}/\tilde{\sigma}_{it}\right)} \quad (7)$$

where the definitions of $\tilde{\omega}_{it}$ and $\tilde{\sigma}_{it}$ are the same as mentioned above, except that all parameters are replaced with estimated values. Here, the adopted logarithmic form is used as the described variable. Therefore, the *IEI* index in this equation denotes the percentage degree of deviation of the actual output from optimal output in the districts, counties, or cities of Beijing, Tianjin, and Hebei.

2.2 Variables and empirical model

2.2.1 Input and output variables

In the C-D production function, the fixed capital stock and labor force of the districts, counties, or cities of Beijing, Tianjin, and Hebei are used as input factors, their regional GDP is used as the output factor, and the three factors constitute input-output indices. The data sources and processing methods of the variables are described as follows:

(1) Fixed capital stock (K). The calculation method from Keller is used (Keller, 2000); specifically, material capital stock is calculated using the equation $K_0 = I_0/(g+\delta)$, where I_0, g, and δ denote the investment amount in the initial year, average growth rate of the investment, and rate of capital depreciation (the δ value is set to 9.6%), respectively. Then, using 2003 as the base year, the original prices of fixed capital in different years are converted in terms of the price index of a fixed investment. Finally, using the perpetual inventory method, the material capital stock of the corresponding years is calculated using the equation $K_t = (1 - \delta) K_{t-1} + I_t (t = 1, 2,\ldots, t-1, t)$. In this equation, K_t denotes the capital stock of the t-th year, and I_t denotes the investment amount of the t-th year. To eliminate the effect of the price factor, the fixed investment amount and GDP of the districts, counties, or cities are converted into their levels from 2003.

(2) Labor force (L). L is defined as the number of employed persons in the districts, counties, or cities. Here, employed persons refer to the people in the population who are engaged in certain social work and earn a certain amount of income.

(3) Regional GDP. Using 2003 as the base year, the GDP deflator of various years is subjected to a smooth adjustment.

2.2.2 Exogenous variables

Economic agglomeration ($Agg_{i,t}$): Some study results indicate that productive efficiency is high in regions where manufacturing is concentrated (Akihiro, 2017), and creative industries agglomeration has a significant and positive impact on regional TFP growth (Hong et al., 2014).The agglomeration level of the regional economy is measured in terms of the regional Gini coefficient, and it is calculated via the equation $G_{ini}{}^{s} = \frac{1}{2(n-1)} \sum_{i=1}^{n}\sum_{j=1}^{n}\left|\lambda_i^s - \lambda_j^s\right|$ (Wen, 2004). In this equation, λ_j^s denotes the proportion people employed in the secondary industry in Region i to the total number of employed people countrywide, and λ_j^s denotes the proportion of employed people in the tertiary industry in Region j to the total number of employed people countrywide.

Human capital ($Hum_{i,t}$): Human capital can actively facilitate economic growth. Specifically, human capital and knowledge-based human capital and knowledge accumulation affect economic growth by affecting productivity and other production factors, respectively (Romer, 1986). The average education years for the population aged six and above in Beijing, Tianjin and Hebei are selected as an index to measure the effect of human capital on the growth of economic efficiency.

Informatization ($Infor_{i,t}$): Informatization is a catalyst that serves to improve economic efficiency. The improvement of the informatization level can transfer information quickly and effectively and reduce time and information cost. The aggregates of the postal and telecommunication business of Beijing, Tianjin, and Hebei are used to measure the effect of the informatization level on economic efficiency.

Industrial structure ($Indus_{i,t}$): Economic growth is manifested not only by the growth of economic aggregates, but also by the transformation and upgrade of the regional industrial structure (Samuels, 2017). Because productivity varies from industry to industry, factors, labor, and capital are transferred from low-productivity industries to high-productivity industries, thus improving the social productivity of each entire industry (Bah and Brada, 2009). The proportion of tertiary industry in Beijing, Tianjin, and Hebei is used to denote the industrial structure in the districts, counties, and cities of Beijing, Tianjin, and Hebei.

Infrastructure ($Infra_{i,t}$): Infrastructure provides an important foundation for economic development and can promote regional economic development through its direct or indirect spillover effect, thus reducing the imbalance of economic development between underdeveloped and developed regions. The infrastructure level is denoted by the per-capita paved road area in Beijing, Tianjin, and Hebei.

Land input ($LS_{i,t}$): Land is consistently considered an important factor that promotes the economic development of China and has a certain active effect on economic growth. Land input is denoted by constructed area in the districts, counties, or cities of Beijing, Tianjin, and Hebei.

Economic opening ($Open_{i,t}$): Economic opening denotes the degree to which the regional economy is open to the outside world and is mainly manifested on the scale of regional opening to the outside world. Active economic opening is manifested as the active economic opening to the outside world and attraction of foreign investment under existing policy conditions. The foreign investment can produce a spillover effect and promote the growth of TFP (Herzer and Donaubauer, 2018). Currently, foreign investment (or to be specific, the year-end total investment amount by foreign-funded enterprises) is usually used as an index to measure the degree of regional economic openness.

Government role ($Gov_{i,t}$): Appropriate governmental intervention in the economy is beneficial for its sound development. However, excessive governmental intervention in the economy will reduce the economic output efficiency, which is contrary to the original intentions. The proportion of government consumption expenditure in the GDP to final consumption expenditure is used to denote the effect of the government on the economic efficiency.

Institutional factors ($Ins_{i,t}$): Thus far, no generally accepted criteria have been established in academia to quantify the effect of institutional factors on economic growth. However, the effect of institutional factors on economic growth is a topic that must be addressed. High-quality economic growth entails not only reasonable resource allocation, but also a set of supportive institutions. The effect of institutions on economic growth is usually denoted as the proportion of total industrial output value in non-state-owned enterprises. Here, the proportion of the output value from non-state-owned enterprises in the total industrial output value is used to reflect the degree of activity of private capital in the market.

2.2.3 Empirical model

(1) Setting of the production function

Based on the significant heterogeneity in economic development of Beijing-Tianjin-Hebei, the following HSFM is built:

$$\ln Y_{it} = \alpha_0 + \alpha_1 \ln K_{it} + \alpha_2 \ln L_{it} + v_{it} - u_{it} \tag{8}$$

(2) Setting of heterogeneity

$$\begin{aligned}\ln \omega_{it} = \beta_0 + \beta_1 \ln Agg_{i,t} + \beta_2 \ln Gov_{i,t} + \\ \beta_3 \ln Hum_{i,t} + \beta_4 \ln Indus_{i,t} + \beta_5 \ln Infor_{i,t} + \\ \beta_6 \ln Infra_{i,t} + \beta_7 \ln Ins_{i,t} + \beta_8 \ln Open_{i,t} + \beta_9 \ln LS_{i,t}\end{aligned} \tag{9}$$

$$\begin{aligned}\ln \sigma^2{}_{it} = \delta_1 + \varphi_1 \ln Agg_{i,t} + \varphi_2 \ln Gov_{i,t} + \\ \varphi_3 \ln Hum_{i,t} + \varphi_4 \ln Indus_{i,t} + \varphi_5 \ln Infor_{i,t} + \\ \varphi_6 \ln Infra_{i,t} + \varphi_7 \ln Ins_{i,t} + \varphi_8 \ln Open_{i,t} + \varphi_9 \ln LS_{i,t}\end{aligned} \tag{10}$$

where Y_{it} denotes the total output, K_{it} and L_{it} denote material capital input and labor input, respectively, v_{it}–u_{it} is the composite error term, v_{it} is the random error term, u_{it} is the technological inefficiency term, α, β, and φ are coefficients to be estimated, and i and t denote a district, county or city, and time, respectively.

The variable data cited herein are from the following statistical yearbooks: 1) China Statistical Yearbook (National Bureau of Statistics, 2004–2017), China City Statistical Yearbook (National Bureau of Statistics, 2004–2017), Beijing Statistical Yearbook (Beijing Municipal Bureau of Statistics, 2004–2017), Hebei Statistical Yearbook (Hebei Municipal Bureau of Statistics, 2004–2017), and Tianjin Statistical Yearbook (Tianjin Municipal Bureau of Statistics, 2004–2017); 2) China Statistical Yearbook for Regional Economy (National Bureau of Statistics, 2004–2017), and China Labor Statistical Yearbook (Ministry of Human Resources and Social Security of the People's Republic of China, 2004–2017). These address the relevant regions from 2004 to 2017 and include government work reports. Notably, Beijing's administrative divisions were adjusted from July 1st, 2010 (specifically, Chongwen District was merged into the Dongcheng District, and Xuanwu District was merged into Xicheng District). Therefore, the related statistical data from 2003 to 2011 were merged during data processing.

2.3 Study area

Beijing-Tianjin-Hebei metropolitan, is not only the political and cultural center of China, but also an important core area of northern China's economy and China's third economic growth pole, include Beijing (Beijing has 16 districts: Dongcheng, Xicheng, Chaoyang, Fengtai, Shijingshan, Haidian, Mentougou, Fangshan, Tongzhou, Shunyi, Changping, Daxing, Huairou, Pinggu, Miyun, Yanqing,), Tianjin (Tianjin has 16 districts: Dongli, Xiqing, Jinnan, Beichen, Wuqing, Baodi, Jizhou, Jinghai, Heping, Hexi, Hebei, Hedong, Nankai, Hongqiao, Ninghe and Binhai New District.), and Hebei Province (Hebei Province has 11 districts and cities, including Baoding, Tangshan, Langfang, Shijiazhuang, Qinhuangdao, Zhangjiakou, Chengde, Cangzhou, Hengshui, Xingtai and Handan), totaling 43 districts, cities and counties. The total area of Beijing-Tianjin- Hebei region is 218 000 km^2, total population of 110 million, and the total regional GDP in 2018 reached 8513.9 billion yuan (National Bureau of Statistics of China, 2019), accounting for 9.45% of the China total GDP.

3 Results and Analysis

3.1 Analysis of HSFM estimates

Considering the stability of the model estimation, evaluation models 1 to 5 (as described in Table 1) were designed according to the parameters related to the economic efficiency of Beijing-Tianjin-Hebei and its

Table 1 Heterogeneity stochastic frontier model estimation and test results

Model	Model 1: no constraints	Model 2: $r = 0$	Model 3: $\delta = 0$	Model 4: $\omega_{it} = 0$	Model 5: $\mu_{it} = 0$
Production function					
ln*K*	1.627***(2.59)	1.386***(2.87)	2.012**(2.26)	2.211***(2.72)	1.053(1.73)
ln*L*	1.124**(2.35)	1.263**(2.23)	1.367***(2.84)	1.082**(1.99)	0.589(1.23)
C	3.153***(3.67)	2.914***(3.54)	2.801***(3.43)	2.842***(3.88)	2.665**(2.56)
Efficiency Loss Mean Equation					
$\ln Agg_{i,t}$	1.972***(2.97)	2.381***(3.04)	2.617*** (3.48)	1.661**(2.49)	
$\ln Gov_{i,t}$	2.584***(3.31)	2.203***(2.61)	2.108** (2.34)	2.002**(2.15)	
$\ln Hum_{i,t}$	1.712***(2.64)	1.815***(2.86)	1.623*** (2.78)	1.513**(2.43)	
$\ln Open_{i,t}$	–0.212*(–1.94)	–0.236(–0.89)	–0.246 (–1.41)	–0.267* (–1.66)	
$\ln Indus_{i,t}$	1.363**(2.22)	1.374**(2.35)	1.462***(2.69)	1.573***(2.88)	
$\ln Infra_{i,t}$	2.087***(2.83)	2.116***(2.92)	2.334***(3.16)	2.432***(3.37)	
$\ln LS_{i,t}$	–0.065(–0.62)	–0.072(–0.53)	–0.064(–0.68)	–0.114(–0.63)	
$\ln Ins_{i,t}$	1.119**(2.47)	1.216*** (2.81)	1.315***(2.96)	1.344***(3.10)	
$\ln Infor_{i,t}$	1.289***(2.71)	0.831*(1.66)	0.849**(1.97)	0.901**(2.33)	
C	3.095***(3.53)	2.932***(3.48)	2.851***(3.41)	2.846***(3.88)	
Efficiency Loss Variance Equation					
$\ln Agg_{i,t}$	2.116***(2.91)	2.419***(3.24)			
$\ln Gov_{i,t}$	2.718***(3.59)	2.303***(3.13)			
$\ln Hum_{i,t}$	1.815*** (2.99)	1.909***(3.05)			
$\ln Open_{i,t}$	–0.097*(–1.68)	–0.085(–1.54)			
$\ln Indus_{i,t}$	1.215**(2.34)	1.252**(2.41)			
$\ln Infra_{i,t}$	2.167***(3.06)	2.204***(3.18)			
$\ln LS_{i,t}$	–1.045(–0.77)	–1.072(–0.84)			
$\ln Ins_{i,t}$	1.337***(2.67)	1.519***(2.87)			
$\ln Infor_{i,t}$	0.954***(2.70)	0.869***(2.63)			
C	2.851***(3.21)	2.732***(3.09)			
Log Likelihood	–396.5	–408.9	–448.6	–476.3	–513.7
LR_1	258.496	235.368	202.189	193.257	–
P	0.000	0.000	0.000	0.000	–
LR_2	–	45.123	102.786	106.729	223.347
P	–	0.000	0.000	0.000	0.000

Notes: ***, ** and * were significant at 1%, 5% and 10% respectively, in parentheses is the *t* value, LR_1, LR_2 are Chi-square values obtained by likelihood ratio test for model 1 to model 5 respectively influencing factors. In model 1, no constraints are imposed on the parameters (no constraints). In model 2, r is assumed to be equal to 0. In model 3, δ is assumed to equal to 0. In model 4, ω_{it} is assumed equal to 0. In model 5, u_{it} is assumed equal to 0. Models 1 to 5 are tested through the log-likelihood ratio. The data show that for the frontier function of economic efficiency, variables (except one or two variables) in the constraint or non-constraint equations pass the 10% significance test. With regard to model design and index selection, the likelihood ratio test (LR test) shows that HSFM 1 is superior to HSFMs 2 to 5, irrespective of whether the original hypothesis is set to 'no environmental constraint (LR_1)' or 'heterogeneous environmental constraint (LR_2)'. Therefore, the calculation results of model 1 were selected for analysis.

According to the frontier function of economic efficiency, capital stock (K) and labor input (L) have a positive effect on regional economic efficiency. Evidently, the economic development of Beijing, Tianjin and Hebei produces a large demand for capital stock because capital stock can effectively stimulate economic development. In the early stage of economic development, based on the internal demand of the people for the expansion of the total amount of material wealth, it is generally believed that the source of economic growth lies in the capital etc, which means that the capital factor input is an important force promoting long-term GDP growth (Li et al., 2017a). In addition, labor input can effectively promote the economic development of Beijing, Tianjin, and Hebei. According to the calculation results of the mean and variance equations for efficiency loss, the economic growth of Beijing-Tianjin-Hebei is significantly positively correlated with economic agglomeration, human capital, industrial structure, government role, institutional factors, infrastructure, and the informatization level. This indicates that economic agglomeration, human capital input, and informatization can significantly reduce the inefficient fluctuation of economic efficiency and improve economic efficiency. Through crisscross network systems, informatization can transform the mode of information transfer from 'hierarchical' to 'flattening'. Implementation of institutions and governmental intervention in the economy will cause inefficient growth of economic efficiency and increase the instability of economic efficiency. Such inefficiency may arise from a misallocation of regional resources. For example, the mismatch between the demand of technological progress for skilled labor and regional skilled labor will affect regional productivity, thus aggravating its inefficiency.

In contrast, economic opening and land input have no significant effect on the economic efficiency of Beijing-Tianjin-Hebei. Generally, foreign investment can promote local investment, thus facilitating economic growth and improving economic efficiency. However, because of high pollution, high energy consumption and low efficiency of foreign enterprises, it poses a certain threat to the regional ecological environment, hindering the promotion of regional green total factor productivity and having a negative effect on regional economic development (Ren et al., 2019). The effect of foreign investment will progressively diminish with time. Some studies have shown that land investment has a significant positive effect on regional economic growth (Zhang and Jin, 2012). Local governments also recognize that a large amount of land investment can bring about rapid economic growth. However, with the intensification of competition for land indicators in various regions, the allocation of resources has been severely distorted, and the disharmony and imbalance of regional resources, environment, and economic development has been aggravated. With the expansion of urban construction, massive land input will cause a scaled diseconomy regarding urban land utilization, thus reducing the economic efficiency.

3.2 Analysis of HSFM estimates for different regions

To determine the differences in economic efficiency between Beijing, Tianjin, and Hebei, we built HSFMs for them and used HSFM 1 for evaluation. The results are provided in Table 2. With regard to the frontier function, the elasticity coefficients of capital input and labor input of Beijing, Tianjin, and Hebei are significantly positive, and capital input contributes to economic growth more significantly than labor input. This reveals that the economic growth trend is evident in Beijing, Tianjin, and Hebei, and capital input is still the main impetus of economic growth in Beijing, Tianjin, and Hebei. During the process of coordinated development of Beijing, Tianjin, and Hebei, it is necessary to improve the efficiency of capital allocation, optimize the industrial structure, and stimulate investment enthusiasm of private capital. In addition, it is necessary to strengthen human resource training, increase labor input, and provide more skill training for workers, thus optimizing the structure of human resources and satisfying the needs of economic development in the new system.

As described in Table 2, in the mean and variance equations of efficiency loss, economic efficiency is positively correlated with economic agglomeration, human capital, industrial structure, infrastructure, and informatization level, whereas it is negatively correlated with government role and economic opening. In addition, economic efficiency is also negatively correlated with land input. Economic agglomeration has a positive effect on the regional economic growth. The results further corroborate the conclusion that human capital has a significant positive effect on economic growth (Scoppa, 2007), even though the positive effect of human capital on economic growth has not been significantly strengthened. However, a study indicates that there is a co-integration between human capital and economic growth in different stages and at different regional heterogeneities. In the period of underdeveloped regional economy, the mutual promotion effect between human capital and economic growth is not evident (Fleisher et al., 2010). In the context of structural reform on the supply side, it is imperative for Beijing, Tianjin, and Hebei to continuously optimize the structure of human resources, integrate the supply-side reform by upgrading human resources, and attain integrated development of human resources in Beijing, Tianjin, and Hebei through appropriate measures (e.g., innovation and entrepreneurship, reform of the educational system, and skill training).

On the surface, the essence of economic growth is the improvement of per capita income and the continuous enrichment of material life, whereas the premise of per capita income improvement is the continuous improvement of productivity. There are two main ways to improve

Table 2 Heterogeneity stochastic frontier model estimation and test results

Region	Beijing	Tianjin	Hebei
Production function			
$\ln K$	1.583^{***} (2.78)	1.617^{***}(3.05)	1.726^{***}(3.27)
$\ln L$	1.364^{***}(2.59)	1.358^{***}(2.65)	1.345^{**}(2.54)
C	3.491^{***}(3.71)	3.347^{***}(3.46)	2.982^{***}(3.22)
Efficiency Loss Mean Equation			
$\ln Agg_{i,t}$	1.417^{**}(2.47)	1.634^{***} (2.85)	1.671^{***} (2.69)
$\ln Gov_{i,t}$	-0.543^{***}(-2.78)	-0.305^{**}(−2.38)	-0.392^{**} (−2.42)
$\ln Hum_{i,t}$	1.309^{**}(2.31)	1.379^{**}(2.46)	1.384^{**}(2.49)
$\ln Open_{i,t}$	-0.312^{**}(−2.30)	-0.276^{**}(−2.27)	-0.419^{***}(−2.61)
$\ln Indus_{i,t}$	1.034^{**}(2.01)	1.635^{***}(2.64)	1.793^{***}(2.86)
$\ln Infra_{i,t}$	1.443^{***}(2.69)	1.514^{**}(2.48)	1.619^{***} (2.63)
$\ln LS_{i,t}$	-1.326^{*}(−1.74)	−0.298(−1.45)	−0.118(−1.16)
$\ln Ins_{i,t}$	1.502^{***}(2.59)	1.496^{**}(2.56)	1.503^{***}(2.60)
$\ln Infor_{i,t}$	1.604^{***}(2.78)	1.795^{***}(2.88)	1.618^{***}(2.83)
C	2.897^{***}(2.81)	3.086^{**}(2.46)	2.792^{***}(3.45)
Efficiency Loss Variance Equation			
$\ln Agg_{i,t}$	1.506^{***}(2.60)	1.414^{**}(2.52)	1.771^{***}(2.78)
$\ln Gov_{i,t}$	-0.379^{**}(−2.48)	-0.345^{***}(−2.59)	-0.456^{***}(−2.67)
$\ln Hum_{i,t}$	1.562^{***}(2.73)	1.533^{***}(2.64)	1.422^{**}(2.41)
$\ln Open_{i,t}$	-0.572^{***}(−2.94)	-0.476^{***}(−2.79)	-0.547^{***}(−2.83)
$\ln Indus_{i,t}$	1.401^{**}(2.48)	1.805^{***}(2.94)	1.819^{***}(2.99)
$\ln Infra_{i,t}$	1.642^{**}(2.57)	1.567^{***}(2.59)	1.794^{***}(2.88)
$\ln LS_{i,t}$	−0.698(−1.06)	−0.729(−1.20)	−0.918(−1.54)
$\ln Ins_{i,t}$	1.612^{***}(2.60)	1.576^{***}(2.59)	1.606^{***}(2.73)
$\ln Infor_{i,t}$	1.654^{***}(2.81)	1.848^{****}(3.46)	1.815^{***}(3.09)
C	2.951^{***}(3.64)	3.136^{***}(3.53)	2.974^{***}(3.19)
Log Likelihood	−338.4	−387.9	−405.7
LR_1	262.503	273.405	299.376
P	0.000	0.000	0.000
LR_2	—	55.204	78.403
P	—	0.000	0.000

Notes: ***, ** and * were significant at 1%, 5% and 10% respectively, in parentheses is the t value labor productivity. One is technological innovation in existing industries; the other is industrial upgrading (Cai et al., 2018). With regard to the industrial structure, the proportion of tertiary industry varies significantly across Beijing-Tianjin-Hebei; however, the structure of tertiary industry continues to improve. The tertiary industry of Beijing and Tianjin has an obvious competitive advantage. Industrial transformation and upgrades improve the economic efficiency of Beijing-Tianjin-Hebei. This is primarily due to the differences in the industrialization process between Beijing, Tianjin, and Hebei. Specifically, Beijing and Tianjin have successively entered the second half of the later stage of industrialization, whereas Hebei is still in the middle stage of industrialization, namely, slow development of industrialization. To attain high-quality economic growth, it is thus imperative that Hebei actively develop a modern service industry and increase industrial transformation, optimization, and upgrades, conforming to the law of industrial evolution and formulating corresponding industrial development policies (He et al., 2018); to invest government capital in the form of state-owned investment companies and guide the transformation of the investment structure and industrial structure (Ping, 2016).

Infrastructure construction strengthens the communication and contacts with the outside world and active affects the economic efficiency (Cao et al., 2019). New economic geography also shows that infrastructure is an important stimulus for economic development, and the construction of a transport infrastructure has a positive effect on economic growth. Research results not only support the above conclusion but also are consistent with the argument that infrastructure is positively correlated with economic growth (Liu and Zhang, 2014; Khanna and Sharma, 2018). This also shows that the integration of a transport infrastructure in Beijing-Tianjin-Hebei not only accelerates the movement of economic factors, but also promotes the economic development of Beijing-Tianjin-Hebei.

Informatization has a positive effect on economic efficiency because information can reduce the operating cost of enterprises and accelerate the communication and contact between different enterprises and different regions. Furthermore, economic growth can be promoted by technological progress and the accumulation of knowledge, which are incident to informatization. Institutions have a positive effect on the economic efficiency. This reveals that the private economy is highly developed in Beijing-Tianjin-Hebei, and that economic efficiency can be significantly improved with a higher proportion of the output value from non-state-owned enterprises in the total industrial output value. Economic institutions can significantly boost economic growth. However, the institutional coefficient value varies significantly between Beijing, Tianjin, and Hebei. The effect of institutions on the private enterprises in Beijing-Tianjin-Hebei has yet to be further explored. In the context of institutional and economic transformation, it is necessary to take the following measures: 1) reduce the governmental intervention in the economy and break the institutional and policy shackles; 2) constantly improve business environments and carry out institutional reform to protect property rights for private economy, thus stimulating the enthusiasm of the private economy; 3) tap the potential of private capital and allow private capital to play a more important role.

As an important dominator of economic activities, governments have an effect on economic development. Research results show that the government role has a negative effect on the economic efficiency of Beijing-Tianjin-Hebei, whereas the negative effect is not statistically significant. This is possibly because governmental intervention in the economy has a certain crowd-out effect on the private sector, causing slow economic efficiency growth. Empirical findings also show that lower levels of regulation are associated with higher TFP growth. Lower barriers to entrepreneurship and lower bureaucratic costs have a positive effect on productivity growth (Escribá-Pérez and Murgui-García, 2018). In the future, governments need to simplify administrative procedures and delegate powers to lower levels, define the list of rights, power, and responsibility, and vitalize the market economy. Regarding the relations between economic opening and economic efficiency, a higher degree of economic opening can improve the ability to attract foreign businesses and investment and introduce advanced technologies and management experience. This is of vital importance for an improvement in regional economic efficiency. Most scholars agree that an open-door policy has a positive effect on economic efficiency (Khanna and Sharma, 2018). Research results show that economic efficiency is not significantly improved by the foreign investment arising from the economic opening of the districts, counties, and cities of Beijing-Tianjin-Hebei. In theory, a higher degree of economic opening can increase the economic aggregate and improve the economic efficiency within a short period in initially constructed or underdeveloped regions. With continuous economic development, however, regional development is no longer an issue of economic aggregates but one of 'quality' improvement (specifically, improvement in economic efficiency). Therefore, it is necessary to continuously optimize the economic structure, industrial structure, and human capital structure, thus maintaining the positive effect of foreign capital on economic development. Research results have shown that land input cannot significantly improve economic efficiency. In the early stage of urban development, more land input can indeed promote the urban economy. With continuous improvement of the urban economic structure, excessive land input will cause a diseconomy of scale for land utilization efficiency; namely, land input has a negative effect on the regional economic efficiency. In an early study, scholars found that the land use system is a complex and 'nature-society-economy' system (Huang et al., 2011). One possible further extension of the land input-output efficiency is the focus on both changes in uses and land use intensity. We still insist that to improve the input-output efficiency of land and promote moderate growth of the regional economy in the future, it is necessary to prevent the diseconomy of scale for land utilization efficiency.

3.3 Analysis of regional economic efficiency in Beijing-Tianjin-Hebei

In the absence of an inefficiency part, the corresponding economic and technological efficiency is 1. In the presence of an inefficiency part, the economic and technological efficiency is less than 1. Therefore, the larger the inefficiency part, the lower the economic and technological efficiency. Based on the HSFM for Beijing-Tianjin-Hebei, we comprehensively measured the other influencing factors of economic and technological efficiency and the consequential inefficiency part, and then measured estimates of the economic and technological efficiency of districts, counties, and cities in Beijing-Tianjin-Hebei. The time span included years from 2003 to 2016 (Fig. 1). The results showed that the economic efficiency of Beijing-Tianjin-Hebei is in the range of 0 to 1.

As shown in Fig. 1, there are spatial differences in the economic and technological efficiencies between the districts, counties, and cities of Beijing-Tianjin-Hebei in 2003 and 2016. Thus, due to the inefficiency part arising from various hypotheses (e.g., economic agglomeration,

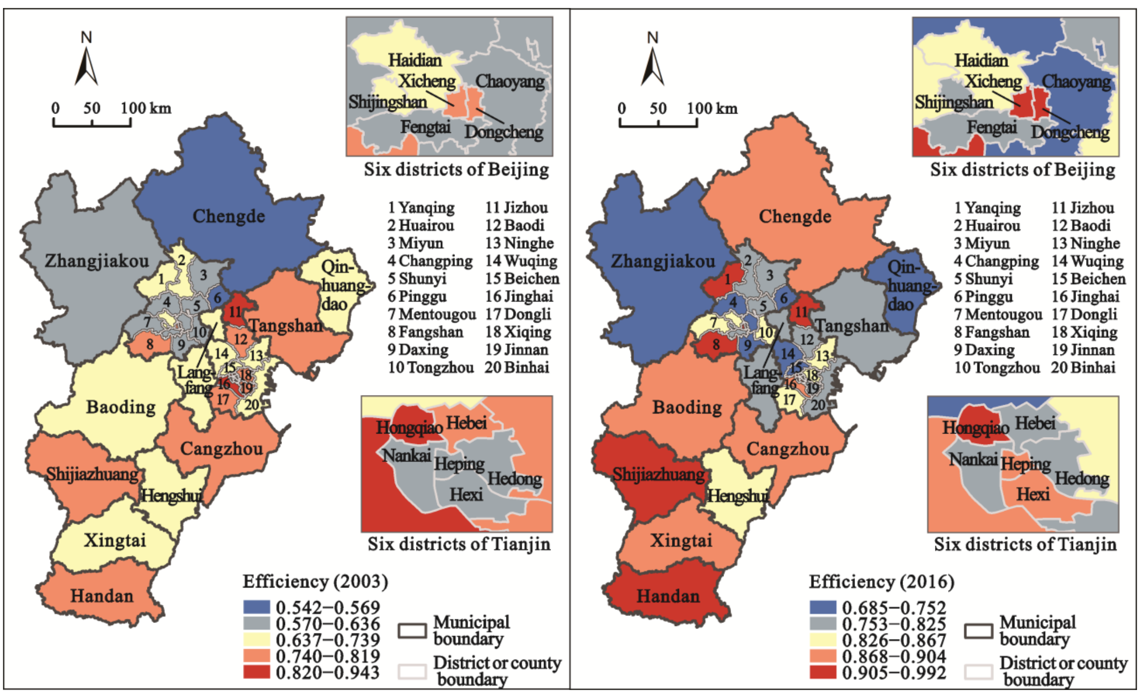

Fig. 1 Estimates of economic and technological efficiency (a. 2003; b.2016) of districts, cities and counties in Beijing-Tianjin-Hebei Metropolitan

governmental role, industrial structure, and economic opening), the overall economic and technological efficiency of Beijing-Tianjin-Hebei is slightly lower than the optimal economic and technological efficiency, which also reveals the imbalance in economic development and low degree of integration within the districts, counties, and cities of Beijing-Tianjin-Hebei. If the effect of such negative factors is further reduced, there is a considerable ability to improve the region's economic efficiency. According to the estimates of economic and technological efficiency of the districts, counties and cities of Beijing-Tianjin-Hebei for 2003 and 2016, there was a significant imbalance in economic efficiency among the districts, counties, and cities of Beijing-Tianjin-Hebei. In 2016, the average economic and technological efficiency of Hebei was the highest (85.30%), followed by Tianjin (83.54%), and the average economic and technological efficiency of Beijing was the lowest (82.32%). This reveals that the efficiency loss arising from inefficiency factors has a significant effect on economic efficiency and economic development of the districts, counties, and cities of Beijing-Tianjin-Hebei.

The research results further revealed that from 2003 to 2016, the increase in the economic and technological efficiency of the districts, counties, and cities of Beijing-Tianjin-Hebei was not high and that the regional economic growth gradually slowed down. In fact, a country or region can attain rapid economic growth within a short period; however, its economic growth will slow down once it surmounts the peak period of economic growth. This also conforms to the fact that China's economic development has entered a new normal stage, characterized by a gradual slowdown in economic growth. Therefore, a slowdown in regional economic growth is also inevitable. In the process of coordinated development, the districts, counties, and cities of Beijing-Tianjin-Hebei must continue restructuring the economy, industry, profit and demand, and technological innovation, and try to improve the efficiency of resource allocation. Data show that in 2016 the average economic and technological efficiencies of Beijing, Tianjin, and Hebei were 0.823, 0.850, and 0.853, respectively. Thus, the economic efficiency of Tianjin and Hebei is overtaking that of Beijing. It is generally believed that to overtake economic development, an improvement in human capital and opening-up is of vital importance.

As described in Table 2, human capital is positively correlated with economic efficiency. This shows that Tianjin and Hebei have had a remarkable effect on the human capital input, or more specifically, their industrial transformation and upgrade are effective. In recent years, in cooperation with Beijing's well-renowned colleges and scientific research institutions, Tianjin and Hebei have enhanced their ability to commercialize scientific and technological achievements, optimized their structure of human resources, and overcome the imbalance in allocation of educational resources. Moreover, continuous industrial upgrade implies reallocation and adjustment of resources, and the upgraded industries need to be underpinned by appropriate human resources. Based on a deep understanding of their own roles, Tianjin and Hebei actively adjust their industrial structure and guide the change in human resource structure. Considering that the effect of the open-door policy on the economic efficiency of Beijing-Tianjin-Hebei continues to diminish, Beijing-Tianjin-Hebei needs to actively respond to and participate in the 'Belt & Road' and the Regional Comprehensive Economic Partnership (RCEP) Project. The intent is to further expand opening-up and build a far-ranging partnership with countries or regions both at home and abroad.

To further investigate the change in economic efficiency within Beijing-Tianjin-Hebei in 2016, this study analyzed the economic efficiency of Beijing, Tianjin, and Hebei. Dongcheng District and Xicheng District are two districts with a high economic and technological efficiency. As Beijing's core districts, they mainly perform the core functions of Beijing as China's political center and cultural center. Although their economic functions are weakening, the two districts have substantial infrastructure and financial supporting facilities, which play an important role in promoting economic development. In addition, the economic efficiency of Tongzhou District has been improved most significantly (0.238). Tongzhou has successively experienced the following transformations: satellite town → new town → Beijing's subsidiary administrative center → Beijing's subsidiary urban center. Owing to capital and labor input, industrial restructuring, economic opening, and active governmental support, Tongzhou has built substantial educational, medical, and transport facilities, ensuring stable economic growth. In 2016, Shijiazhuang and Handan of Hebei had the highest economic and technological efficiency (0.942 and 0.939, respectively). The integrated development of Beijing-Tianjin-Hebei brought about regional economic integration. This provided development opportunities to Shijiazhuang, Handan and Hebei's other cities. In Shijiazhuang, the scale of private economy continues to expand, industrial agglomeration is accelerated together with the construction of industrial parks and industrial transformation and upgrades, and economic growth is rapid. By taking appropriate measures (e.g., transform government functions, improve the investment climate, and implement industrial transformation and upgrades), Handan has attracted large quantities of funds and human resources, thus promoting economic development. In 2016, Hongqiao District and Jixian County of Tianjin had a high economic efficiency. In terms of efficiency improvement, the economic efficiency of Heping District and Hexi District improved the most. Overall, the economic efficiency of Tianjin's central urban districts is quite high. With the establishment and development of some economic function zones, Tianjin's economic center has begun to transfer, thus improving its economic efficiency. As Tianjin has taken over the functions transferred from Beijing and carries out the Belt & Road Initiatives, some industries have been transferred from central districts to peripheral districts that are deficient of a substantial auxiliary service industry. This aggravates industry hollowing in the central districts. Therefore, addressing the relations between industry hollowing and economic development is an issue that needs to be considered.

4 Discussion

China's economy has entered a stage of high-efficiency growth. In this stage, the industry model is characterized by the integration of capital, human resources, and innovation. Innovation has become the core-driving factor for the improvement of regional economic efficiency, and economic development has been stepping toward high-efficiency growth. Based on this analysis, the following recommendations are put forward:

At the macroscopic level: 1) First, management organizations should be improved. Beijing-Tianjin-Hebei can set up offices under the leadership of coordinated development specifically responsible for the coordination of the three regions, implement the decision-making of the Central Government and Beijing, Tianjin, and Hebei on coordinated development, formulate coordinated development and construction plans, improve the coordinated policy system, and promote the construction of major projects. 2) Considering the development status and functional orientation of different regions, Beijing should take the opportunity of coordinated development of Beijing, Tianjin, and Hebei, further evacuate the non-core functions, address the 'big-city disease', and evacuate the excessive population. Tianjin should initiate a permanent residency of talented persons project, take the opportunity of the Belt & Road Initiative, speed up industrial transformation and upgrades, highlight R&D and innovation of advanced manufacturing industry, strengthen the construction of a shipping center, and focus on planning a high-end service industry (Lu, 2015). Hebei should focus on human capital (e.g., initiate a permanent residency of talented persons project and provide more economic support for highly educated and highly skilled talents), deepen the supply-side reform, take various development opportunities (e.g., coordinated development of Beijing, Tianjin and Hebei, Belt & Road, construction of the Xiongan New Area, and Winter Olympic Games 2022), open up international markets, and introduce funds, management experience, and advanced technologies from both home and abroad, thus promoting high-quality economic growth.

At the microscopic level: 1) Economic intervention should be reduced and fund management platforms should be built (e.g., venture capital and private equity investment), and improve fund support. Further the growth potential of labor and capital should be stimulated, especially private capital, creating new demographic bonus and rationally guiding the factors flow in Beijing-Tianjin-Hebei regions. 2) A linkage mechanism for talented persons from three regions should be built. The fundamental strategic resources for economic and social development lie in human resources. Beijing, Tianjin, and Hebei should optimize the regional human resources structure and improve its flow system. Optimization of the construction of talent team can be achieved through the implementation of talented circle project. Promotion of high-end talents gathering and cross-regional employment should be enforced. In the comprehensive demonstration areas, industrial pilot projects and service institutions pilot projects should be planned by the government, and the talents who are employed should be given allowance to work in different places according to the income gap between regions. Moreover, a database can be constructed by experts from Beijing, Tianjin, and Hebei, and the governments can build a high-level talent exchange and sharing platform, providing a good environment for talent flow in the three regions. 3) Infrastructure construction should be strenghtened. According to the requirement of the Beijing-Tianjin-Hebei coordinated development strategy, transportation integration is one of the key areas to break through first. The interconnection of a transportation system can create good conditions for the industrial relief and transfer, and provide strong support for the coordinated development of the three regions. The construction of the Beijing-Tianjin and Beijing-Hebei Expressway, Intercity Railway, and Expressway should be sped up in an all-round way.

5 Conclusions

From the perspective of TFP, we built heterogeneity SFPFs for Beijing, Tianjin, and Hebei by using panel data from 2003 to 2016. The intent was to investigate the coordination of regional economic factors and the effect of production factors on the regional economic efficiency. The conclusions are summarized as follows:

(1) Overall, the economic and technological efficiency of Beijing-Tianjin-Hebei has tended to increase in a periodic manner. There has been an obvious imbalance in the economic efficiency between different districts, counties and cities, and economic growth has slowed. The economic development of Tianjin and Hebei has mainly relied upon capital input and a cheap labor force.

(2) The HSFPFs of Beijing, Tianjin, and Hebei are different from each other, and investment remains an important impetus of economic growth for Beijing-Tianjin-Hebei. In terms of economic developmental stages, Beijing has led Tianjin and Hebei. In terms of the mode of action, the production factors of Beijing and Tianjin were superior to those of Hebei (specifically, economic growth benefited from large-scale input of production factors), however the goodness of fitting was not high in the coordinated development of different regions. Compared with Beijing and Tianjin, the input of production factors in Hebei did not bring about large-scale output, and the economic growth in Hebei has mainly relied upon massive capital input.

(3) According to the mean and variance equations for regional economic efficiency loss, economic efficiency is positively correlated with economic agglomeration, human capital, industrial structure, infrastructure, the informatization level, and institutional factors but not significantly correlated with the government role and economic opening. Because of different functional orientations, Beijing, Tianjin, and Hebei focused on different production factors. Therefore, the economic agglomeration effect and economic efficiency have not significantly improved, although industrial transformation and upgrade have been attained.

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