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Investment performance measurement of new generation mobile communication networks based on dynamic DEA model

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Abstract

With the fast development of the mobile internet in recent years, the new generation mobile communication networks as the basic supporting have received widespread attentions. During the upgrading period of new generation networks, the telecom operators need to grasp the network investment performance, which is one of the key factors for deploying the new generation networks and arranging new services effectively. In this paper, first, we propose a method based on the dynamic DEA model and the sensitivity analysis to measure the network investment performance of telecom operators, which gives the managers and researchers insight into the changing process of the key influence factors on the investment performance. Then, we build the input-output indicators system of the DEA model from five dimensions, such as INVESTMENT, SUPPLY, ADOPTION, USAGE, and REVENUE, for a more complete and valid characterization to the network investment performance. At last, we apply the proposed method to conduct an empirical research on the operational data of one Chinese telecom operator from 2013 to 2015, which has been the initial launch phase of 4G network. Based on the result, we develop effective investment strategies for the upgrading period of networks, which also gives guidelines for the investment of 5G and other new generation networks in the future.

Keywords: Performance measurement, New generation networks, Telecom investment, DEA model, Sensitivity analysis

1 Introduction

Recently, the new generation mobile communication networks (hereinafter referred to as "new generation networks"), such as 3G, 4G, and 5G, play an important role in the advancement of mobile internet and have received a vital concern [1–3]. During the upgrading period of new generation networks, telecom operators tend to keep an eye on the network investment performance, which is one of the key factors for deploying the new generation networks and arranging new mobile data services (hereinafter referred to as "new service") effectively [4, 5]. Network investment performance is an important component of performance measurement for telecom operators, which means degree of the force that investment portfolios of different network facilities driving the operational performance improvement [4, 6, 7].

The methods for telecom performance measurement have been relatively mature in the recent years. Exploratory factor analysis and principal components analysis have been used widely in the performance measurement when the number of sub-indices and the relationships among them cannot be obtained through management experience and theory analysis. Structural equation modeling (SEM) is also a commonly used performance measurement method in telecommunication [8, 9]. Unfortunately, this method has been used only for analyzing the static data in previous studies. In this case, data envelopment analysis (DEA) model appears to have a significantly advantage over the other performance measurement methods from the point of efficiency [10–12].

In this paper, we propose a method based on the dynamic DEA model and the sensitivity analysis to measure the network investment performance of telecom operators. Then, we build the input-output indicators

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system of the DEA model from five dimensions to measure the network investment performance more effectively. Finally, we make an empirical research to dynamically analyze 4G investment of one Chinese telecom operator, and the practical investment strategies during the upgrading period of the networks can be summarized, which can also give investment guidelines for 5G and other new generation networks in the future.

2 Related work

2.1 Insight into telecom investment

The investment in telecommunications infrastructure and network facilities is both an important handgrip to improve the services of telecom operators and the important foundation of local economic development [4, 5]. While more studies are aiming at telecom investment in the recent years, Aude et al. [13] analyzed a large number of investment cases of Telecom Multinational Enterprises in Africa from 2000 to 2015, found there had been existed a big gap between the final deal prices and local market contexts, and then analyzed the key factors that influencing deal prices. With mobile telecommunication investment cases in Africa from 2001 to 2011, Goodiel et al. [14] tried to provide a framework to analyze the influence factors of telecom investment. Based on the operational data of 23 European operators from 2003 to 2012, Wolfgang et al. [7] proposed a flexible accelerator model to analyze the investment of broadband service and investigated the effects of market competition and strategies on telecom investment. During the upgrading period of new generation networks, network investment performance is the key factor for the deployment of the new generation networks and also the important power to drive the new services. Unfortunately, there are few researches focused on this point.

2.2 Performance measurement of telecom services

The methods to measure the operational performance of telecom services have been developed very well in the recent years. Exploratory factor analysis and principal components analysis have been used commonly in the specific situation of performance measurement. Based on product market regulations and employment protection legislation, Nicoletti et al. [15] established an indicators system where factor analysis had been used to aggregate detailed indicators into a summary indicator, and components were weighted according to its contribution to the overall variance in the data. To measure the performance of telecom infrastructure, Adnan et al. [16] proposed providing a composite Telecommunication Index (TI) based on principal component analysis including a number of telecommunication sub-indices, such as fixed telephone networks, the Internet, and mobile networks. As the two methods are data-driven, management experience is hard to be considered in the modeling. Hence, they can only be deployed in the situation where the number of sub-indices and the relations among them cannot be obtained by management experience and theory analysis.

Another method that is been commonly used in performance measurement is structural equation modeling (SEM). To assess the availability, adoption, and use of telecommunication networks and services at the country level, Gerpott and Ahmadi [8] provided a second-order composite index (TDI). This indicator and sub-indices weights are calculated by the SEM method. And the weights of indicators or sub-indices entering into an overall TDI are varying with the socio-economic target criterion. To measure broadband development in the EU, Lemstra and Voogt [17] developed a performance index and a market model where the statistically significant factors and components in the path model were determined by SEM method. SEM can be also deployed in calculating the weight of indicators and sub-indices, and one or several overall indices measuring the performance of telecom operators. Unfortunately, SEM method is used more often to analyze static data in previous literature.

Recently, DEA model is used by many researchers to study the relative efficiency of telecom services. To obtain the efficiency rankings of operators, Debnath and Shankar [10] calculated the relative efficiency of Indian telecom operators based on DEA. To measure the efficiency of Taiwan telecom operators from 2001 to 2005, Yang and Chang [11] used a constant and variable returns to scale-based method. In order to increase the number of decision-making units, DEA window analysis is introduced in this research. To study the key factors influencing Indian consumers' buying behavior of telecom services, Kumar and Shankar [12] developed a framework based on fuzzy AHP and DEA model. Compared with other methods of performance measurement, DEA model appears to have a significantly advantage over the other methods from the point of efficiency.

3 Methodology

Constant returns to scale model (CRS) and variable returns to scale model (VRS) are the basic model of DEA [18, 19]. In CRS model, suppose the number of decision-making units (DMU) is n, the number of inputs and outputs is m and s. Denote the inputs and outputs as $X_j = (x_{1j}, \cdots, x_{ij}, \cdots, x_{mj})^T$ and $Y_j = (y_{1j}, \cdots, y_{rj}, \cdots, y_{mj})^T$ respectively, with $i = 1, \cdots, m$, $r = 1, \cdots, s$ and $j = 1, \cdots, n$.

We need to endow appropriate weight for every inputs and outputs, the weights of X_i and Y_r are recorded as v_i and u_r. Define $V = (v_1, \cdots, v_m)^T$ and $U = (u_1, \cdots, u_s)^T$. Then, the efficiency evaluation index of DMU_j can be defined as follows:

$$h_j = \frac{U^T Y_j}{V^T X_j} = \frac{\sum_{r=1}^{s} u_r y_{rj}}{\sum_{i=1}^{m} v_i x_{ij}}, j = 1, \cdots, n, \tag{1}$$

Next, we can evaluate the efficiency of DMU_{j_0} $(1 \leq j_0 \leq n)$, and the *CRS model* as follows:

$$(\overline{P})\left\{ \begin{aligned} & \max \frac{\sum_{r=1}^{s} u_r y_{rj0}}{\sum_{i=1}^{m} v_i x_{ij0}} = V_{\overline{P}} \\ & s.t. \frac{\sum_{r=1}^{s} u_r y_{rj}}{\sum_{i=1}^{m} v_i x_{ij}} \leq 1, \quad j = 1, \cdots, n \\ & u_r \geq 0, \quad r = 1, \cdots, s \\ & v_i \geq 0, \quad i = 1, \cdots, m \end{aligned} \right. \tag{2}$$

By Charnes-Cooper transform [18, 20, 21], we can set the following variables:

$$\left\{ \begin{aligned} t &= \frac{1}{V^T X_0} \\ \omega &= TV \\ \mu &= TU \end{aligned} \right. \tag{3}$$

Equation (2) can be transformed to an equivalent linear programming problem, as follows:

$$(P)\left\{ \begin{aligned} & \max \mu^T Y_0 = V_P \\ & s.t. \varpi^T X_j - \mu^T Y_j \geq 0, \; j = 1, 2, \cdots, n \\ & \varpi^T X_0 = 1 \\ & \omega \geq 0, \mu \geq 0 \end{aligned} \right. \tag{4}$$

On the basis of the dual algorithm for general linear programming, the dual programming of the model (*P*) can be transformed as follows:

$$(D^0)\left\{ \begin{aligned} & \min \theta = V_{D^0} \\ & s.t. \sum_{j=1}^{n} \lambda_j X_j + \theta X_0 \leq 0 \\ & \sum_{j=1}^{n} \lambda_j Y_j \geq Y_0 \\ & \lambda_j \geq 0, \quad j = 1, \cdots, n \end{aligned} \right. \tag{5}$$

Then, the slack variables should been introduced into the model above, such as $s^+ \geq 0, s^- \geq 0, s^+(s_1^+, s_2^+, \ldots, s_s^+)$, $s^-(s_1^-, s_2^-, \ldots, s_m^-)$, and the *input – DEA model* as follows:

$$(D^1)\left\{ \begin{aligned} & \min \theta = V_{D^1} \\ & s.t. \sum_{j=1}^{n} \lambda_j X_j + s^- = \theta X_0 \\ & \sum_{j=1}^{n} \lambda_j Y_j - s^+ = Y_0 \\ & \lambda_j \geq 0, \quad j = 1, \cdots, n \\ & s^+ \geq 0, \quad s^- \geq 0 \end{aligned} \right. \tag{6}$$

The *CRS model* can be revised to *VRS model* by adding an assumption of convexity [19], i.e., $\sum_{i=1}^{n} \lambda_i = 1$, as shown in the following:

$$(G^1)\left\{ \begin{aligned} & \min \theta = V_{G^1} \\ & s.t. \sum_{j=1}^{n} \lambda_j X_j + s^- = \theta X_0 \\ & \sum_{j=1}^{n} \lambda_j Y_j - s^+ = Y_0 \\ & \sum_{j=1}^{n} \lambda_j = 1 \\ & \lambda_j \geq 0, \quad j = 1, \cdots, n \\ & s^+ \geq 0, \quad s^- \geq 0 \end{aligned} \right. \tag{7}$$

The *CRS model* and *VRS model* can be used to calculate the technical efficiency (TE) and pure technical efficiency (PTE) of each DMU, and scale efficiency (SE) can be calculated as follows:

$$\text{scale efficiency (SE)} = \frac{\text{technical efficiency (TE)}}{\text{pure technical efficiency (PTE)}} \tag{8}$$

4 Experiments

4.1 Data description and preparation

The original dataset used in this study contains monthly operating data from 31 provincial companies of one Chinese telecom operator during the years 2013–2015. The preprocessing of time series data commonly involves two steps: handling missing values and eliminating seasonal effects. Firstly, linear interpolation method has been used to replace few missing values in the dataset [22]. Then we use Classical Seasonal Decomposition by Moving Averages method to eliminate seasonal effects in the dataset, which decomposes a time series data into seasonal, trend, and irregular components [23].

4.2 Experimental design

In order to measure the network investment performance more effectively, the input indicators of the DEA model should be cover variety of telecom investments in network facilities, and the output indicators should be set to describe the operational performance of telecom services completely and validly [8, 24]. Therefore, we build the input-output indicators system of the DEA model (shown in Table 1) from five dimensions, such as INVESTMENT, SUPPLY, ADOPTION, USAGE, and REVENUE. The investment indicators (such as “I1 investment in wireless access network,” “I2 investment in transmission network,” “I3 investment in service network,” “I4 investment in supporting network,” and “I5 investment in construction”) have been used as the inputs, which could cover variety of telecom investments in network facilities. To fully describe the operational performance of provincial companies, we grouped the outputs into four sub-indices labeled SUPPLY, ADOPTION, USAGE, and REVENUE [4, 8, 25]. SUPPLY measures the quality of networks to support telecom services, which includes two indicators: “S1 mobile phone exchange capacity” and “S2 size of carriers.” ADOPTION is about the user size of telecom service and has been occurred frequently in the previous studies [8, 26–28]. In this study, ADOPTION sub-area includes two indicators: “A1 customer size” and “A2 customer size of cellular data service.” USAGE measures the usage size of telecom services. Many researchers use the indicators of market penetration in this sub-area, such as the number of Internet users per 100 inhabitants [26, 29, 30]. However, it is inappropriate because there are wide differences among the consumer behaviors of telecom services [31]. In this sub-area, “U1 calls duration per month” and “U2 cellular data traffic per month” have been used. REVENUE sub-area includes the “R1 revenue per month” and “R2 revenue of cellular data service per month,” which are the oriented indicators of telecom services development.

Table 1 The inputs and outputs of the DEA model

Inputs	Outputs
INVESTMENT	SUPPLY
I1 investment in wireless access network	S1 mobile phone exchange capacity
I2 investment in transmission network	S2 size of carriers
I3 investment in service network	ADOPTION
I4 investment in supporting network	A1 customer size
I5 investment in construction	A2 customer size of cellular data service
	USAGE
	U1 calls duration per month
	U2 cellular data traffic per month
	REVENUE
	R1 revenue per month
	R2 revenue of cellular data service per month

The correlation test has been validated between inputs and outputs above, and the results are shown in Table 2. All of the correlation coefficients reject the null hypothesis on the 0.01 significance level, and it means that the inputs and outputs of the model are reasonable.

For this Chinese telecom operator, years 2013–2015 were the upgrading period of 4G network, and the period of most telecom projects was 1 year, such as base station construction and assessment. Therefore, this period could be divided into three annual stages: (1) This Chinese telecom operator begun building large-scale trial 4G networks and launching pre-commercial service in 2013, so we named year 2013 as “preparation stage.” (2) In 2014, 4G networks have been officially on use, and the operator obtained 1-year window to develop 4G without competition. Thus, year 2014 was named “the first year and the window stage.” (3) This Chinese telecom operator entered into “competition stage,” when the competitors launched their 4G service in 2015. The following parts would focus on the network investment performance of these three stages and summarize the investment strategies during the inception phase of the new services, which can give investment guidelines for 5G and other new generation networks.

4.3 Empirical results and discussion

4.3.1 Network investment performance analysis

As explained in Section 3, network investment performance contains three aspects: technical efficiency (TE), pure technical efficiency (PTE), and scale efficiency (SE). The annual average TE, PTE, and SE of 31 provincial

Table 2 The correlation test between inputs and outputs of the model

		I1	I2	I3	I4	I5
S1	Pearson correlation	0.535	0.666	0.388	0.392	0.392
	Sig. (two-tailed)	0.000	0.000	0.000	0.000	0.000
S2	Pearson correlation	0.600	0.705	0.390	0.354	0.412
	Sig. (two-tailed)	0.000	0.000	0.000	0.000	0.000
A1	Pearson correlation	0.586	0.723	0.418	0.400	0.424
	Sig. (two-tailed)	0.000	0.000	0.000	0.000	0.000
A2	Pearson correlation	0.584	0.725	0.422	0.399	0.418
	Sig. (two-tailed)	0.000	0.000	0.000	0.000	0.000
U1	Pearson correlation	0.569	0.716	0.425	0.411	0.423
	Sig. (two-tailed)	0.000	0.000	0.000	0.000	0.000
U2	Pearson correlation	0.470	0.542	0.232	0.241	0.303
	Sig. (two-tailed)	0.000	0.000	0.000	0.000	0.000
R1	Pearson correlation	0.579	0.708	0.446	0.393	0.434
	Sig. (two-tailed)	0.000	0.000	0.000	0.000	0.000
R2	Pearson correlation	0.628	0.671	0.377	0.300	0.377
	Sig. (two-tailed)	0.000	0.000	0.000	0.000	0.000

companies from 2013 to 2015 are shown in Table 3. Provincial company of Guangdong has consistently held the top spot for the 3 years, and the TE of Zhejiang, Jiangsu, Shandong, Sichuan, Henan, and Hebei has also been significantly higher than the other provincial companies. For simply research, we divide the all provincial companies into two groups depending on their TE, the above 7 companies are named group A, and the others are group B.

The annual average TE, PTE, and SE of two groups from 2013 to 2015 are shown in Fig. 1. Group A is better overall than group B in investment performance during the upgrading period of new generation networks. The result shows that the two groups do not have great difference in PTE, but have great difference in SE. This illustrates that group B should increase the investment during the upgrading period, and then the investment performance could be improved.

The TE of group A experienced the development process from slow decline to rapid growth, which presents V-shape tendency: The TE achieved 0.670 by 2014 and rose substantially in 2015, climbing to 0.777. The TE of group B experienced from stability to rapid growth, the lowest point was 0.276 in 2013, and peaked at 0.356 in 2015.

In respect of PTE, both group A and B present V-shape tendency: The PTE of group A reached its lowest point in 2014, and the next year increased to 0.857, which beyond the 2013 level. Group B also reached its nadir in 2014, and the next year went back to the level

Table 3 The annual average technical efficiency (TE), pure technical efficiency (PTE), and scale efficiency (SE) of 31 provincial companies from 2013 to 2015

	Year 2013			Year 2014			Year 2015		
	TE	PTE	SE	TE	PTE	SE	TE	PTE	SE
Guangdong	0.931	0.986	0.945	0.882	0.975	0.905	0.954	1.000	0.954
Sichuan	0.853	0.897	0.950	0.797	0.846	0.941	0.821	0.847	0.966
Jiangsu	0.653	0.736	0.882	0.642	0.716	0.892	0.809	0.817	0.990
Hebei	0.642	0.812	0.786	0.600	0.788	0.759	0.661	0.861	0.767
Zhejiang	0.628	0.785	0.794	0.636	0.743	0.854	0.844	0.866	0.973
Shandong	0.601	0.764	0.786	0.618	0.783	0.786	0.693	0.784	0.884
Henan	0.558	0.772	0.714	0.517	0.731	0.707	0.655	0.827	0.789
Fujian	0.416	0.742	0.557	0.429	0.750	0.570	0.514	0.757	0.673
Liaoning	0.405	0.776	0.518	0.366	0.757	0.483	0.506	0.762	0.655
Anhui	0.403	0.768	0.524	0.364	0.738	0.493	0.460	0.771	0.596
Hunan	0.393	0.765	0.511	0.372	0.732	0.505	0.457	0.775	0.589
Hubei	0.385	0.753	0.512	0.383	0.723	0.529	0.497	0.776	0.639
Yunnan	0.381	0.765	0.497	0.372	0.729	0.509	0.556	0.837	0.661
Neimenggu	0.375	0.770	0.486	0.384	0.762	0.503	0.376	0.745	0.504
Shanghai	0.370	0.743	0.496	0.361	0.752	0.480	0.409	0.752	0.545
Beijing	0.351	0.745	0.470	0.401	0.769	0.514	0.506	0.790	0.635
Guizhou	0.337	0.773	0.421	0.290	0.764	0.379	0.364	0.766	0.472
Xinjiang	0.308	0.810	0.378	0.348	0.770	0.452	0.491	0.803	0.592
Guangxi	0.307	0.796	0.386	0.310	0.741	0.418	0.374	0.752	0.496
Heilongjiang	0.298	0.739	0.404	0.444	0.782	0.567	0.470	0.766	0.614
Shanxi	0.295	0.770	0.383	0.302	0.731	0.412	0.430	0.756	0.548
Shaanxi	0.294	0.767	0.382	0.307	0.736	0.417	0.382	0.756	0.506
Jiangxi	0.283	0.757	0.374	0.326	0.720	0.452	0.393	0.716	0.549
Chongqing	0.241	0.780	0.309	0.234	0.761	0.307	0.289	0.754	0.383
Jilin	0.231	0.793	0.290	0.209	0.775	0.269	0.406	0.796	0.489
Gansu	0.177	0.773	0.228	0.185	0.774	0.239	0.237	0.800	0.296
Tianjin	0.143	0.815	0.176	0.131	0.807	0.163	0.146	0.816	0.178
Hainan	0.100	0.829	0.121	0.096	0.826	0.116	0.112	0.832	0.134
Ningxia	0.059	0.831	0.070	0.056	0.834	0.066	0.063	0.819	0.077
Qinghai	0.047	0.831	0.056	0.058	0.799	0.073	0.073	0.806	0.091
Xizang	0.035	0.856	0.040	0.033	0.856	0.038	0.043	0.856	0.050

of 2013, reaching 0.782. It is shown that the technical ability of provincial companies falls slightly in the first year and window stage, subject to the influence of the networks update, and will be returned back in the competition stage. Group A is significantly more efficient than group B, and the PTE in the competition stage goes beyond the preparation stage. However, the PTE of group B in the competition stage has almost same number compared with the preparation stage.

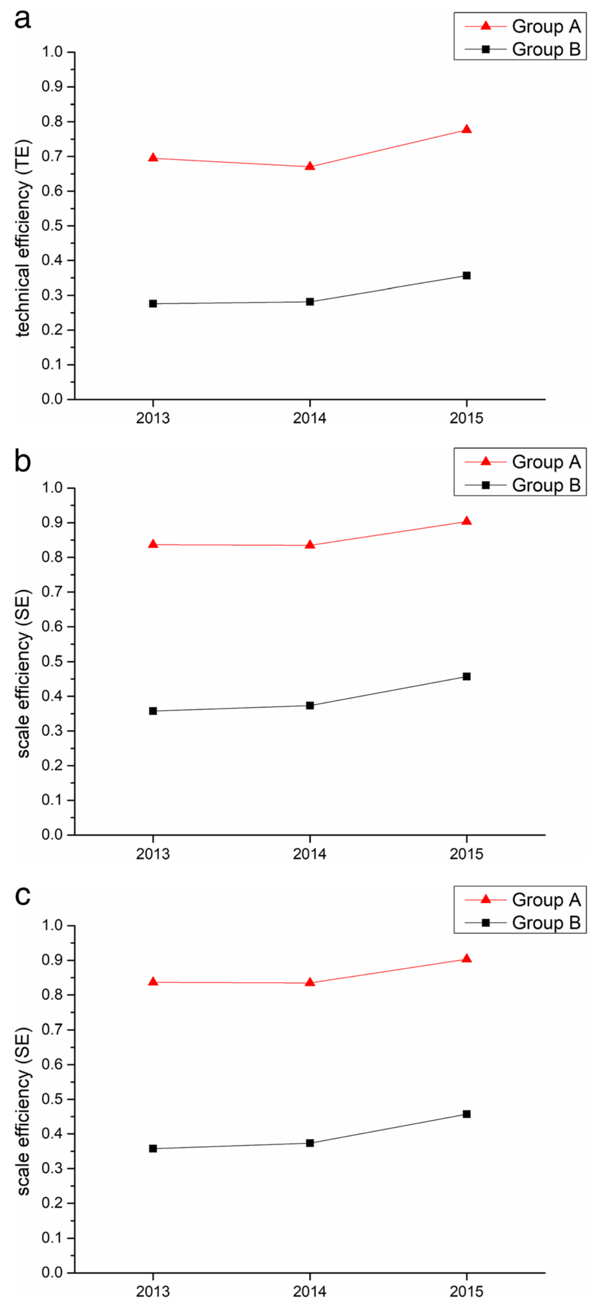

Fig. 1 The annual average TE, PTE, and SE of two groups from 2013 to 2015. **a** The annual average TE of the two groups from 2013 to 2015. Red line with up-triangle indicates the annual average TE of group A from 2013 to 2015. Black line with square indicates the annual average TE of group B from 2013 to 2015. **b** The annual average PTE of the two groups from 2013 to 2015. Red line with up-triangle indicates the annual average PTE of group A from 2013 to 2015. Black line with square indicates the annual average PTE of group B from 2013 to 2015. **c** The annual average SE of the two groups from 2013 to 2015. Red line with up-triangle indicates the annual average SE of group A from 2013 to 2015. Black line with square indicates the annual average SE of group B from 2013 to 2015

In respect of SE, both group A and B experienced from stability to rapid growth: The SE of group A achieved 0.835 by 2014 and rose substantially in 2015, climbing to 0.903. The lowest point of group B was 0.358 in 2013 and peaked at 0.457 in 2015. Besides, the proportions of diseconomies scale DMUs which due to increasing returns to scale (IRS) [18, 19] in group A from 2013 to 2015 were 79.76%, 84.52%, and 73.80%, on the other hand, the proportions of group B were 99.65%, 100.00%, and 99.31%. This illustrates that lots of provincial companies in group A need properly raise the investment in the preparation and window stages. Most of provincial companies in group B should increase investment in all of three stages, so as to improve the network investment performance during the upgrading period of new generation networks.

4.3.2 Influential factors analysis on network investment performance

We deleted the inputs separately and put the other inputs into DEA model, and then calculated the percentage of difference between the new TE and the old one in order. These percentages represent the sensitivity of TE to the each input [32–34]. Generally speaking, the bigger the sensitivity coefficients, the more sensitive the investment performance is to the investment indicator, so that this indicator becomes more crucial to improve performance. The sensitivity of investment performance to each input investment indicator from 2013 to 2015 is shown in Fig. 2.

From 2013 to 2015, the investment performance of all provincial companies is most sensitive to the wireless access and transmission network investment. To guarantee the new services running smoothly, provincial companies should pay more attention to the wireless access and transmission network investment during the inception phase. The sensitivity of all provincial companies to the investment in wireless access network showed descend trend, and the sensitivity of group A is significantly higher than group B. It means that the wireless access network investment should be mainly focused on the prophase of the new services. Due to the larger number of users and better foundation of market, group A is more urgent for the new wireless access network. The sensitivity of all provincial companies to the investment

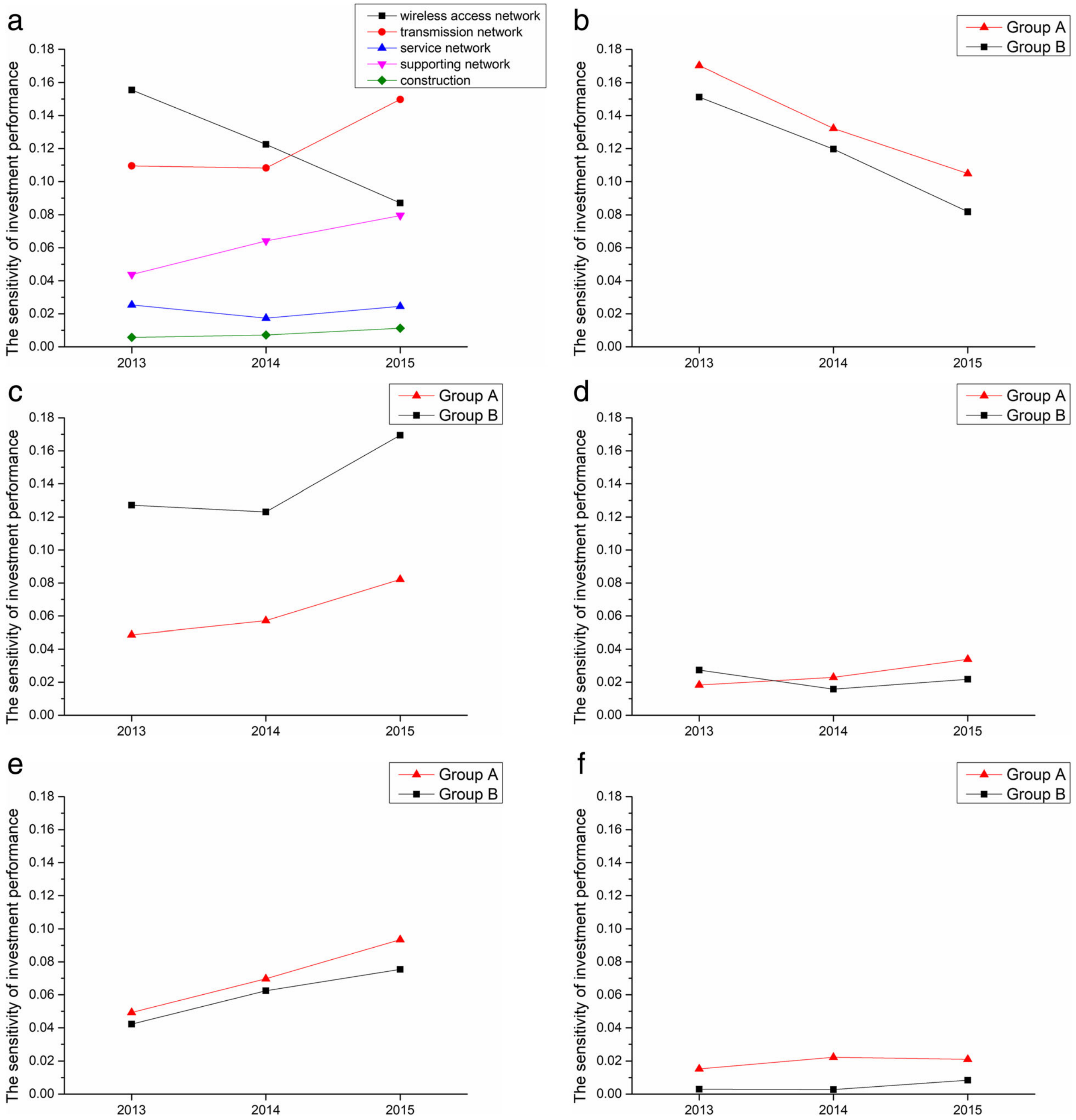

Fig. 2 (See legend on next page.)

(See figure on previous page.)

Fig. 2 The sensitivity of investment performance to each input investment indicator from 2013 to 2015. **a** The sensitivity of investment performance of all provincial companies to each input investment indicator from 2013 to 2015. Black line with square indicates the sensitivity of investment performance to the investment in wireless access network. Red line with circle indicates the sensitivity of investment performance to the investment in transmission network. Blue line with up-triangle indicates the sensitivity of investment performance to the investment in service network. Purple line with down-triangle indicates the sensitivity of investment performance to the investment in supporting network. Green line with diamond indicates the sensitivity of investment performance to the investment in construction. **b** The sensitivity of investment performance of groups A and B to the investment in wireless access network from 2013 to 2015. Red line with up-triangle indicates the sensitivity of investment performance of group A to the investment in wireless access network. Black line with square indicates the sensitivity of investment performance of group B to the investment in wireless access network. **c** The sensitivity of investment performance of groups A and B to the investment in transmission network from 2013 to 2015. Red line with up-triangle indicates the sensitivity of investment performance of group A to the investment in transmission network. Black line with square indicates the sensitivity of investment performance of group B to the investment in transmission network. **d** The sensitivity of investment performance of groups A and B to the investment in service network from 2013 to 2015. Red line with up-triangle indicates the sensitivity of investment performance of group A to the investment in service network. Black line with square indicates the sensitivity of investment performance of group B to the investment in service network. **e** The sensitivity of investment performance of groups A and B to the investment in supporting network from 2013 to 2015. Red line with up-triangle indicates the sensitivity of investment performance of group A to the investment in supporting network. Black line with square indicates the sensitivity of investment performance of group B to the investment in supporting network. **f** The sensitivity of investment performance of groups A and B to the investment in construction from 2013 to 2015. Red line with up-triangle indicates the sensitivity of investment performance of group A to the investment in construction. Black line with square indicates the sensitivity of investment performance of group B to the investment in construction

in transmission network increased appeared slowly first and fast afterwards, and the sensitivity of group B is significantly higher than group A. It illustrates that the transmission network investment should be based on the development of the new services. The original transmission network only need modified slightly by the requirement of new services; thus, the transmission network investment of provincial companies should be based on the original network. By the weakness of original transmission network, the investment demand of group B is higher.

The underlying trend for the sensitivity of all provincial companies to the investment in supporting network rose steadily, and the sensitivity of group A is significantly higher than group B. There is a high correlation between the supporting network investment demand and the development of new services, so that the investment strength should be increased gradually with the new services promotion, avoiding with up-front investment lower investment performance. The sensitivity to the service network investment exists some difference in groups A and B: the sensitivity of group A showed rising trend; meanwhile, group B was more stable. With the better foundation of the market, group A innovates the product range and business model of the new services at first, and the demand of service network investment could be driven.

The sensitivity of all provincial companies to the construction was the lowest, and the sensitivity of group A is a little higher than group B. During the inception phase of the new services, the construction is the lowest priority investment compared with the basic network.

5 Conclusions and future works

In this paper, we propose a method based on the dynamic DEA model and the sensitivity analysis to measure the network investment performance of telecom operators, which can give the managers and researchers insight into the changing process of the key influence factors on the network investment performance. Then, we build the input-output indicators system of the DEA model from five dimensions, such as INVESTMENT, SUPPLY, ADOPTION, USAGE, and REVENUE, for a more complete and valid characterization to the network investment performance. At last, we apply the proposed method to conduct an empirical research on the operational data of one Chinese telecom operator from 2013 to 2015, which has been the initial launch phase of 4G network, and the practical investment strategies during the upgrading period of new generation networks can be summarized as follows: (1) Provincial companies of telecom operators should pay more attention to the wireless access and transmission network investment during the upgrading period. (2) The wireless access network investment should be mainly focused on the prophase of the new services. (3) In general, provincial companies fall into two groups according to their investment performance, leading group named group A, and the other named group B. Group A is more urgent for the new wireless access network. (4) The transmission network investment should be based on the development of the new services and original network. By the weakness of original transmission network, the investment demand of group B is higher. (5) Supporting network investment should be increased gradually with the new services promotion, avoiding with up-front investment lower investment performance. (6) Group A innovates the product range and business model of the new service at first, and the demand of service network investment could be driven. (7) The construction is the lowest priority investment compared with the basic networks.

In future work, more dimensions of outputs could be introduced into the model. Researchers can use this model to 5G investment empirical study, and some of the investment strategies would be improved.

Abbreviations

CRS: Constant returns to scale model; DEA: Data envelopment analysis; DMU: Decision-making units; IRS: Increasing returns to scale; PTE: Pure technical efficiency; SE: Scale efficiency; SEM: Structural equation modeling; TE: Technical efficiency; TI: Telecommunication Index; VRS: Variable returns to scale model

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Authors' contributions

YD is the main writer of this paper. He proposed the main idea and analyzed the result. XZ gave good suggestions on the innovation of the paper. ZL and LW put forward some suggestions for the design of the experimental part. All authors read and approved the final manuscript.

Availability of data and materials

The datasets analyzed during the current study are not publicly available since involved a confidentiality agreement but are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

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