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Evaluation of Technological Innovation Efficiency in Chinese High-tech Industry: Two-stage Relational DEA

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Abstract: When using DEA method to evaluate the innovation efficiency of High- tech industry, the traditional approach takes it as a "black box", regardless of the internal sub-processes and their influences on the overall system efficiency. This study decomposed the high- tech industrial innovation system into two interrelated chain stages and calculated the overall efficiency and sub-stage efficiencies based on the two-stage relational DEA model under constant return to scale. Furthermore, this study measured correlation degree in high- tech industrial innovation system and classified high-tech industries into four types.

Key words: High-tech industry, technological innovation efficiency, two-stage relational DEA model, coordination degree

INTRODUCTION

With the rapid development of high-tech in the 21st century, high-tech industry has become the core of modern economic growth. Governments attach great importance to R and D investment in high-tech industry. Statistical results show that annual growth rates of China's 2000-2010 high-tech industry R and D fund and full-time equivalent of R and D personnel are 24.17 and 15.86%, respectively. In the contrast, the growth rate of sales revenue from new products is merely 6.85%. Compared with developed countries, China's high-tech industry is in relative shortage of innovation resources and it is difficult to sustain high levels of investment. Therefore, the study on innovation efficiency of high-tech industry would be a valuable part.

High-tech industry technological innovation is a complex process which is a production system evolving in multiple-inputs and multiple-outputs.It is very difficult to measure the absolute efficiency. Thus, scholars mostly focus on the evaluation of the relative efficiency, using a method of Data Envelopment Analysis (DEA) initially proposed by Charnes *et al*. (1978). The studies can be divided into the nation comparison of different years, regions and inter-industry comparison. In recent years, analysis of innovation efficiencies between different high-tech industries is becoming a new research hotspot. Traditional DEA methods take technological innovation process in high-tech industry as a "black box", using initial inputs and the final outputs to evaluate relative efficiencies of Decision-making Units (DMUs), without considering the relationship between divisions (Chen *et al*., 2006; Guan and Chen, 2009). with the understanding of innovation process and innovation value chain, researchers began to focus on not only high technology development, but also the economic transformation of technology. Therefore, two-stage DEA model was introduced to deal with this issue (Yin *et al*., 2004; Huang, 2009). They evaluated the overall efficiency and divisional efficiencies of each stage by establishing different "gray model" (two-stage DEA model). However, it didn't consider the correlation between two sub-processes and the impact on the overall system efficiency. Network DEA model was originally proposed by Fare and Grosskopf (1996, 2000) and the two-stage DEA is one of the simplest forms. As a method of efficiency measurement with complex structure, the essence of the Network DEA model is to split the internal production processes and examine the impacts of each stage on the overall efficiency. Seiford and Zhu (1999), Luo (2003) and Chen and Zhu (2004) have tried to use network DEA models to deal with practical problems and made some new results.

These studies went deep into the production system, however they took various stages of the production process as independent sub-systems without considering the series relationship of stages linked by intermediate products. Therefore, the evaluation results did not reflect the actual situation of production. The rational two-stage DEA model took into account two sub-processes impacts on overall efficiency by setting same weights of same elements to reflect the linkage between sub-processes and decomposed the overall efficiency into the product of the efficiencies of the sub-processes (Kao, 2009). This new

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DEA model began to receive attention, but existing researches focus only on the measurements of banking efficiency and insurance companies performances based on capital operation, few studies in other areas (Huang *et al*., 2009; Cheng and Feng, 2008; Kao and Hwang, 2008).

In this study high-tech industry technological innovation system was decomposed into two sub-sequential stages and two-stage DEA model under variable returns was used to estimate China's 17 high-tech industries innovation efficiencies and the relational coefficient of two phases. Moreover, the research calculated coordination degree between the technology development phase and commercialization phase. The analysis has great meaning to the optimization and adjustment of China's high-tech industrial structure. Meanwhile it would be helpful to enhance the international competitiveness of high-tech industry.

TWO-STAGE RELATIONAL DEA

Suppose there are n decision-making units, each decision-making unit is divided into a series of two sub-processes. Assume that each DMU_i (i = 1, 2, ..., n) has m inputs to the first stage, i.e., $X_i = (x_{i1}, x_{i2}, \ldots x_{im})^T$ and k outputs from the first stage, i.e., $Z_i = (z_{i1}, z_{i2}, \ldots, z_{ik})^T$. These k outputs are the whole inputs to the second stage. The outputs from the second stage are $Y_i = (y_{i1}, y_{i2}, \ldots, y_{is})^T$

Considering the relationship between two sub-processes, a model must satisfy the following two conditions: Condition 1, for each sub-process the cumulative outputs do not exceed the cumulative inputs; condition 2, the intermediate products are outputs generated by stage1 as while as inputs to stage 2 and they have same multiplier δ^T. Therefore, a relational two-stage DEA model can be express as:

$$E = \max\left(\left(u^T Y_i + \sum_{d=1}^{2} \mu_i^{(d)}\right)\right) / v^T X_i$$

$$\text{s.t.}\begin{cases} u^T Y_j + \sum_{d=1}^{2} \mu_i^{(d)} - v^T X_j \le 0 \; j = 1, 2, \cdots, n \; (1.1) \\ \delta^T Z_j + \mu_i^{(1)} - v^T X_j \le 0 \; j = 1, 2, \cdots, n \; (1.2) \\ u^T Y_j + \mu_i^{(2)} - \delta^T Z_j \le 0 \; j = 1, 2, \cdots, n \; (1.3) \\ u \ge \varepsilon e_s, v \ge \varepsilon e_m, \delta \ge \varepsilon e_k, \mu_i^{(1)}, \mu_i^{(2)} \in R^1 \end{cases}$$

Then the whole process satisfies constraint (1.1), sub-processes satisfy constraints (1.2) and (1.3) respectively. Moreover, the same elements in the model have same weight which meets the above condition 2. From economic point of view, the weights can be seen as shadow prices of elements. Through analyzing the model (1), it can be further found that the sum of constraints (1.2) and (1.3) exactly equals to the constraint (1.1). Let:

$$t = 1\frac{1}{v^T X_i}, \mu = tu. \varphi = t\delta. \omega = tv. \eta_i^{(1)} = t\mu_i^{(1)}$$

Model (1) can be transformed as follow:

$$E = \max u^T Y_i + \sum_{d=1}^{2} \eta_i^{(d)}$$

$$\text{s.t.}\begin{cases} \varphi^T Z_j + \eta_i^{(1)} - \omega^T X_j \le 0 \; j = 1, 2, \cdots, n \\ \mu^T Y_j + \eta_i^{(2)} - \varphi^T Z_j \le 0 \; j = 1, 2, \cdots, n \\ \omega^T X_i = 1 \\ \mu \ge \varepsilon' e_s, \omega \ge \varepsilon' e_m, \varphi \ge \varepsilon' e_m, \eta_i^{(1)}, \eta_i^{(2)} \in R^1 \end{cases}$$

After the optimal solution $\mu^*, \omega^*, \varphi^*, \eta_i^{(1)}, \eta_i^{(2)}$ is found, the efficiencies are obtained subsequently as:

$$E = \mu^{*T} Y_i + \sum_{d=1}^{2} \eta_i^{(d)*}$$

$$E^{(1)} = (\varphi^{*T} Z_i + \eta_i^{(1)*}) / \omega^{*T} X_i$$

$$E^{(2)} = (\mu^{*T} Y_i + \eta_i^{(2)*}) / \varphi^{*T} Z_i$$

EMPERITAL STUDY

Two-stage process in high-tech industrial innovation: The high-tech innovation process is a complex series of activities involving concept generation, evaluation of the concept, research and development (R and D), implementation and final distribution. From the perspective of the entire industry, the outputs of innovation system are mainly technology and products. Technology as the immediate product is the result of R and D as well as a precondition of product development

Therefore, the whole production process of the high-tech industry can be divided into two stages: technology development and commercialization. The first stage is characterized by R and D, where high-tech is ultimately generated in the forms of patent and non-patent. This stage mainly reflects the technology development efficiency, that is, conversion efficiency of investment into technological achievements. The second stage is the continuation of the first stage and it includes the whole process of technological achievements into products, where technological achievements are applied to production for profit.

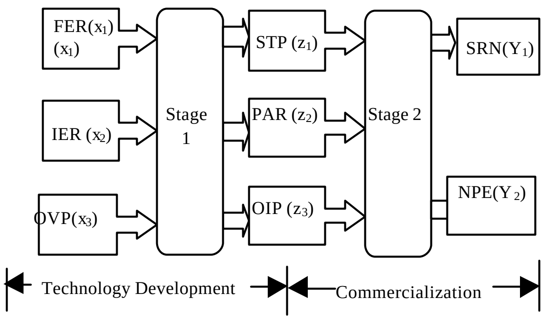

Fig. 1: Two-stage process in high-tech innovation

Therefore, the high-tech innovation process can be decomposed into two relational sub-systems with multi-inputs and multi-outputs. The efficiency of first stage measures the performance in technology acquisition while the efficiency of the second stage measures the performance in commercialization. Based on reviewing the literature£¬this study created the input-output indicators in two sub-processes of high-tech innovation as shown in Fig. 1:

- **The inputs of system are:** Full-time equivalent of R and D personnel (FER):The sum of full-time staffs and staffs converted by workload into full-time staffs
- **Intramural expenditure for R and D (˜IER):** All actual expenditures for independent R and D activities during the reporting period
- **Original value of productive equipment (OVP):** Monetary expenses on construction, acquisition, installation, renovation and expansion
- The outputs of technology development stage as well as the inputs of commercialization stage are:
- **SandT projects (STP):** All projects involving R and D activities, application of R and D acquisitions and technical service that come into operation that year
- **Patent applications received (PAR):** Accepted patent applications which are filed to patent authorities
- **Owning inventive patent (OIP):** Patents granted by the patent authorities
- The outputs of system which are also the outputs of commercialization stage are:
- **Sales revenue from new products (SRN):** Sales income of new products during the report period
- **New Product Exports (NPE):** Revenue from selling new products to the foreign trade sector for export and selling directly to foreign merchants in the reporting period

APPLICATION

In accordance with the OECD and China's high technology industry classification, The five categories of high-tech industries are further subdivided into 17 specific industries, specific affiliation in Table 1. Research data came from China Statistics Yearbook on High Technology Industry2008~2010,this study used MATLAB7.1 to solve the corresponding results which are shown in Table 2.

Overall efficiency and sub-process efficiency measurement: The Overall efficiency of 17 segments of Chinese high-tech industries is low, with an average of 0.5080 and eight industries have lower efficiencies than average, accounting for 47.06% of the whole ranking. MBTE and MOE perform efficiently at the highest level of 1.0000. MCM, MFTCHM and MEC have the lowest efficiency scores less than 0.1500. The inefficiency of high-tech industry innovation will be attributed to technological backwardness and organizational management. Therefore, the establishment of market-oriented innovation chain by accelerating the transformation of development pattern and industrial restructuring is critical to enhance the core competitiveness of high-tech industry.

For the first stage, namely technology development sub-process, 17 sectors have an average score of 0.7038. Nine industries get lower efficiency scores than the average, accounting for 52.94% of all the industries which indicates the majority have problems in technology development sub-process. Specifically, MCE, MDTSRR, MECR and MOE perform effectively in technology development stage with efficiency values of 1.0000. MRA and MEC have efficiency scores less than 0.4000, indicating that sub-process of technology development perform inefficiently in the two sectors, there may be a serious waste of innovation resources. For example: There is considerable capital invested in MRA during technology development process , however, a small part can be effectively transformed into scientific and technological achievements due to a lack of core technology and limited research capacity.

The second stage, namely the commercialization sub-process, essentially evaluates the combination of technology and market demands. MCPE and MOE are most effective in sub-process 2, of which the efficiency values are 1.0000. Economic transformation obtain efficiency scores in MFTCHM and MS less than 0.1000 which indicate that the innovation activities of two sectors in second stage do not brought favorable profits. China has got a brilliant achievement in spacecraft

Table 1: Five main High-tech industries and their divisions

High-tech Industry	Division
Manufacture of Medicine (MM)	Manufacture of Chemical Medicine(MCM), Manufacture of Finished Traditional Chinese Herbal Medicine (MFTCHM), Manufacture of Biological and Biochemical Chemical Products(MBBCP)
Manufacture of Aircrafts and Spacecrafts (MAS)	Manufacture and Repairing of Airplanes(MRA), Manufacture of Spacecrafts(MS)
Manufacture of Electronic Equipment and Communication Equipment (MEECE)	Manufacture of Communication Equipment(MCE), Manufacture of Radar and Its Fittings(MRF), Manufacture of Broadcasting and TV Equipment(MBTE), Manufacture of Electronic Appliances(MEA), Manufacture of Electronic Components (MEC), Manufacture of Domestic TV Set and Radio Receiver(MDTSRR), Manufacture of Other Electronic Equipment(MOEE)
Manufacture of Computers and Office Equipments (MCOE)	Manufacture of Entired Computer (MECR), Manufacture of Computer Peripheral Equipment (MCPE) Manufacture of Office Equipment (MOE)
Manufacture of Medical Equipments and Measuring Instrument (MMEMI)	Manufacture of Medical Equipment and Appliances (MMEA), Manufacture of Measuring Instrument (MMI)

Table 2: Efficiency values for high-tech industry divisions

	Relational Two-stage DEA Model		
High-tech Industry	E	$E^{(1)}$	$E^{(2)}$
MCM	0.1236	0.4211	0.2689
MFTCHM	0.1645	0.7564	0.0790
MBBCP	0.5432	0.5432	0.2722
MRA	0.1259	0.2407	0.4538
MS	0.8960	0.8960	0.0557
MCE	0.3861	1.0000	0.3861
MRIF	0.6488	0.6488	0.2192
MBTE	1.0000	1.0000	0.5885
MEA	0.2660	0.6757	0.3889
MEC	0.1337	0.3807	0.3410
MDTSRR	0.4661	0.7895	0.5904
MOEE	0.7604	0.9134	0.5512
MECR	0.7740	1.0000	0.7740
MCPE	0.5703	0.5703	1.0000
MOE	1.0000	1.0000	1.0000
MMEA	0.5804	0.5804	0.3015
MMI	0.1967	0.5386	0.2186
AVERAGE	0.5080	0.7038	0.4411

manufacturing which stems from inputs of advanced technology and orderly management in the first stage. However, a huge difference exists between China's civilian aerospace industry and other space powers-the former shows a significant disconnection from marketing. Obviously, aerospace industry has greatly promoted the development of China's science, technology and talent cultivation, while it is economic benefits that encourage a sustainable development in the long run.

MOE is the only DMU which has two efficient stages leading to overall efficiency. For the whole high-tech industry, the average efficiency scores of overall process, sub-process 1and sub-process2 are, respectively 0.5080, 0.7038 and 0.4411 which indicates that Chinese high-tech industry has much room for improvement in innovation process.

Table 3 Variance coefficients of two-stages

High-tech industry	VC value	High-tech industry	VC value
MCM	0.905	MEC	0.994
MFTCHM	0.117	MDTSRR	0.959
MBBCP	0.791	MOEE	0.881
MRA	0.821	MECR	0.968
MS	0.049	MCPE	0.856
MCE	0.646	MOE	1.000
MRIF	0.570	MMEA	0.810
MBTE	0.870	MMI	0.675
MEA	0.860		

Coordination degree in high-tech innovation process: Coordination degree is an indicator to measure whether the coupling of two sub-processes is in good condition or not. In practical applications, coordination degrees were classified into several types according to variance coefficients of technology development efficiency $E^{(1)}$ and commercialization efficiency $E^{(2)}$ which were used to describe coordination degree, the definition is as follows:

$$VC = \frac{\left|E^{(1)} - E^{(2)}\right|}{\left(E^{(1)} + E^{(2)}\right)/2}$$

Since $E^{(1)}>0$ $E^{(2)}>0$, when, ,VC takes its minimum value. So VC can be formulated as:

$$\left[E^{(1)}E^{(2)} / \left(\frac{E^{(1)} + E^{(2)}}{2}\right)^2\right] \rightarrow \max$$

where, $k \geq 2$, obviously, $0|VC \leq 1$ .It has been proved by mathematical theory, only when $E^{(1)} = E^{(2)}$two sub-stages have the maximum coordination degree. We used above model to test the coordination degrees of two sub-stages in 17 subdivisions. According to VC values, 17 industries can be grouped into four types illustrated in Table 3.

- High coordination. MOE, MEC, MECR, MDTSRR and MCM are included, VC values of which lie between 0.9~1.0. MOE, MDTSRR and MECR perform quite effectively both in two sub-stages and which indicates that innovative mechanisms in these industries, especially innovative resource allocation mechanism works well. They are marching in the effectively intensive innovation. MCM and MEC are in high coordination. On the contrary both the two sub-stages have poor efficiency scores. This may be caused by non-efficiency-driven investment in technology development phase, besides managers do not attach much importance to the degree of transformation from technology into marketing

- Coordination. MOEE, MBTE MEA, MCPE, MRA and MMEA are included ,VC values of which lie between 0.8~0.9. Experiencing a range of stages of copying, co-operation and self-designed innovation, these industries have discovered relatively complete innovation patterns. However, independent innovation will play a leading role in the long run. Thus, enhancing the core factors in efficiency to optimize development patterns is a key direction in future evolution
- Weak coordination. MBBCP, MMI and MCE are included, VC values of which lie between 0.6~0.8. Innovation activities in above industries are quite frequent, MCE has a technology development efficiency score (1.000) in the forefront in high-tech industry. However, the outputs of innovation and innovation resources do not match because of ineffective allocation of resources. These industries should emphasis the development of market demands, turning technical achievements into profits
- Uncoordinated. MRIF, MFTCHM and MS are included, VC values of which lie between 0~0.6. Two sub-stage efficiencies in these industries are extremely uneven which shows a departure from normal. Analysis results denote that industries of this type have relatively high efficiencies in first sub-process but low efficiencies in second sub-process which means a perfect mechanism of investment in R and D. However, due to a bottleneck or omission point in the process of innovation development, namely technology development divorced from marketing, innovation activities do not bring economic benefits

CONCLUSION

High-tech industrial innovation system has significant features of chain-link process. Considering characteristics during the process, this study decomposed high-tech innovation system into two continuous sub-phases of technology development and commercialization which are linked by intermediate products. Taking 17 Chinese high-tech industries for samples, this study used relational two-stage DEA model to measure overall efficiency, sub-process efficiencies in the innovation process. The study also presented coordination degree between technology development stage and commercialization stage. The analysis results indicate that Chinese 17 high-tech industries have relatively low efficiency whether in whole innovation process or in sub-process and there still is much room for improvement. The research classified 17 high-tech industries as four types according to coordination degree and made a corresponding analysis.

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