Chapter 7
Capital Stock and Performance of R&D Organizations: A Dynamic DEA-ANP Hybrid Approach

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Abstract Assessing resource allocation in R&D organizations is an important issue that requires a comprehensive measure to characterize it. To provide a greater picture, we first construct a dynamic three-stage network DEA model, which evaluates the R&D efficiency, technology-diffusion efficiency, and value-creation efficiency of Taiwanese R&D organizations over the period 2005–2009. Before integrating window analysis and network data envelopment analysis (DEA) to estimate dynamic efficiencies, we apply Analytic Network Process (ANP) to determine the relative importance of each stage. Subsequently, we employ panel data regression to examine whether the capital stock of patents, quality of human resources, and capability of service support affect the dynamic efficiencies of the R&D organizations. Our findings show that the mean R&D efficiency score is greater than that of the technology-diffusion efficiency, with the value-creation efficiency score being the lowest, suggesting that R&D organizations have to firstly work on improving the technology-diffusion inefficiency, and finally improving the value-creation inefficiency. Our panel data regression analysis indicates that the

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capital stock of patents do affect the efficiencies of the R&D organizations, even including the quality of human resources and capability of service support. That is, managers should focus on technological development and innovation to improve their corporate performance.

Keywords Network data envelopment analysis • Analytic Network Process • Window analysis • R&D organizations • Patents

7.1 Introduction

From the perspective of a dynamic and three-stage data envelopment analysis (DEA) procedure, this study integrates window analysis and network DEA as well as Analytic Network Process (ANP) to evaluate the research and development (R&D) efficiency, technology-diffusion efficiency, and value-creation efficiency of Taiwanese R&D organizations over the period 2005–2009. This study further investigates changes in the efficiency scores of the R&D organizations in different industries from a long-term perspective. Furthermore, from the viewpoint of organizational innovation, this study examines the impacts of the capital stock of patents, quality of human resources, and capability of service support on the performance of the R&D organizations. This relation is a key input into the continuing discussion on the role of innovation in corporate performance. Recent years have seen a shift in attention from a focus on labor-intensive environment to an emphasis on emphasizing knowledge-intensive environment (Efrat 2014), whereby technological development has become a key factor in a country's competitiveness. That is, countries around the world formulate policies to encourage the development of science and technology as well as their innovation in order to sustain economic growth. In this regard, R&D organizations play a vital role in achieving technological innovation in a country (Lu and Hung 2011).

In this study, we focus our analysis on Taiwan because it serves as a suitable setting to examine the above-stated purposes. In 2007, the Science, Technology and Industry Scoreboard released by the Organization for Economic Cooperation and Development (OECD) documents that most of the OECD countries including Taiwan prioritize technology and innovation in stimulating economic growth. In fact, Taiwan has progressed from a labor-intensive economy to a capital-intensive and technology-intensive economy since the 1950s. Taiwan has long emphasized the development of technology and innovation in its modernization and economic development plans. In today's challenging world, Taiwan continues to focus on developing a knowledge-intensive economy to cope well in the intense global competitive environment. According to the 2009 World Economic Forum, Taiwan has moved into the innovation-oriented period from innovation-oriented transitional period. Among the initiatives implemented by the Taiwanese government are: (i) promoting the collaboration between players in the practice and academicians, (ii) providing small and medium enterprises (SME) with consultations on innovative R&D technology, (iii) developing new technological and innovative services, and (iv) reducing the gap on technology among industrial player, to name but a few of the ventures by the country.

With the increasing emphasis on technological development and innovation, requirements for performance evaluation of R&D organizations have become more critical. Despite its obvious importance, academic studies to date do not adequately address the question of how to objectively quantify and benchmark the performance of national R&D organizations. This study addresses the issue, making several important contributions to the literature. Through analyses on R&D efficiency, technology-diffusion efficiency, and value-creation efficiency, we provide insights to assist governments in implementing performance improvement strategies to enhance competitive advantage of R&D organizations. Note also that we employ ANP analysis to obtain the relative weights for each stage of efficiency from the average scores given by five R&D managers, which are then used in the DEA analysis. Furthermore, this paper examines changes in the efficiency performance of the R&D organizations in different industries from a long-term perspective.

To effectively evaluate efficiency changes over time, a researcher can employ several data envelopment analysis (DEA) models such as window analysis (Klopp 1985), the Malmquist index (Färe et al. 1994), and the dynamic slacks-based measure (SBM) (Tone and Tsutsui 2010). DEA is a non-parametric method that utilizes mathematical programming to evaluate the relative efficiency of decision making units (DMUs) via simultaneous handling of multiple variables (Cooper et al. 2006). Note that performance evaluation is a complex process that requires more than a single criterion to characterize it, suggesting that a uni-dimensional performance measure is not capable of comprehensively assess an organization's performance evaluation (Hung et al. 2013; Zhu 2009). However, the traditional DEA approach not only neglect changes in efficiency across several periods, but also disregard intermediate measures or linking activities (Chen and Zhu 2004; Tone and Tsutsui 2009). To address the problem, we integrate window analysis (Klopp 1985) and a network DEA model (Tone and Tsutsui 2009). Specifically, we evaluate the performance of Taiwanese R&D organizations through a hybrid approach based on a dynamic network DEA and ANP.

For the first time, as far as we know, we also document the impact of the capital stock of patents on R&D efficiency, technology-diffusion efficiency, and value-creation efficiency. This effect is present even including quality of human resources and capability of service support in our panel data regression models, with the exception of value-creation efficiency. In the last decade, we have seen mounting evidence of the usefulness of the capital stock of patents. For example, Guellec and Bruno (2004) and Wang and Huang (2007) argue that the capital stock of patents serves as an indicator to understand the competitive advantage and ultimately the performance of an organization.

The remainder of this study is organized as follows. Section 7.2 discusses the literature on the current status of Taiwanese R&D organizations and DEA applications in R&D organizations. Section 7.3 describes the research design of this study. Section 7.4 presents the results. A final section concludes the paper.

7.2 Literature Review

7.2.1 Current Status of Taiwanese R&D Organizations

R&D organizations are research institutes established by government to develop effective technology improvement plans and to transfer their technological development and innovation to industries (Edquist 1997). R&D organizations play an important role in the innovation system of a country, whereby they coordinate and execute R&D activities in the country. To ensure ordered allocation of national resources and to rapidly grow SMEs' skills and knowledge in their industries, R&D organizations are also responsible to help SMEs to engage in R&D projects of government-owned corporations.

In Taiwan, the Department of Industrial Technology of the Ministry of Economic Affairs has established many R&D organizations like Institute for Information Industry, Development Center for Biotechnology, Metal Industries Research & Development Center, Food Industry Research & Development Institute, Taiwan Textile Research Institute, Cycling & Health Industry R&D Center, United Ship Design & Development Center, Stone & Resource Industry R&D Center, Printing Technology Research Institute, Plastics Industry Development Center, Precision Machinery Research Development Center, Medical and Pharmaceutical and Development Center, Footwear & Recreation Technology Research Institute, and Animal Technology Institute Taiwan, all of which are to support industrial development, to build the high-tech industries in Taiwan, to achieve technological development and innovation, and ultimately to improve the nation's competitive advantage.

Another R&D organization in Taiwan is Chung Shan Institute of Science and Technology (CSIST) under the Ministry of Defense. Since 1969, CSIST have been developing many systems and architects of national defense; even though it is no longer a military unit, it is still an important resource of defense technology of Taiwan. Its key R&D activities include the areas of electronics, information warfare, and advanced weapon system. It positively interacts with other major research institutes in Taiwan, and expands its R&D activities to many universities in order to boost academic involvement in the national defense technology. Under government policy, CSIST actively joins research projects on technological development and focuses their target on technologies that are beneficial to military and civilian.

Although various works have been completed to investigate the operating performance of R&D organizations, there is little convincing evidence that examines the dynamic performance of R&D organizations. In the first stage, this study integrates window analysis and network DEA to evaluate the performance of R&D organizations in terms of R&D efficiency, technology-diffusion efficiency, and value-creation efficiency, a three-stage DEA analysis. Through this innovative approach, we not only can understand differences in managerial performance of R&D organizations, but also can find out efficiency changes of R&D organizations over long-term periods. This study aims to provide such information with insights into resource allocation that could help managers in making strategic decision to improve their competitive advantage.

7.2.2 DEA Applications in R&D Organizations

Research into the effects of R&D investment on improving productivity has a long history (see for example, González and Gascón 2004; Griliches 1988; Hartmann 2003; Mansfield 1980, 1988; Saiki et al. 2006; Walwyn 2007). Lee and Park (2005) argue that measuring R&D productivity is a prerequisite for improving R&D productivity. Using the DEA approach, the authors measure the relative R&D efficiency of Asian countries. Since R&D policy is an important national agenda, we contend that evaluation of resources allocation and value creation of R&D organizations in a country should be highlighted, in line with the study by Lee et al. (2009) that evaluates the efficiency of national R&D programs. Other studies have also applied DEA to examine relative R&D efficiency across countries, including the US and Japan (Co and Chew 1997), European countries (Rousseau and Rousseau 1998), and developed and developing countries (Sharma and Thomas 2008).

Among all, Rousseau and Rousseau (1997) are among the first scholars to recommend the use of DEA for estimating the relative national/inter-countries R&D efficiencies. After that, the two similar scholars apply DEA again to gauge the R&D efficiency of European countries (Rousseau and Rousseau 1998). Another early study by Co and Chew (1997) on applying DEA to take into consideration R&D expenditures is another effective study that answers the question of whether firms in the U.S. or those in Japan perform better. Other subsequent DEA-application studies (for example, Nasierowski and Arcelus 2003; Wang and Huang 2007) apply a two-step approach, in which they regress environmental factors on R&D efficiency. Besides individual efficiency analysis, they also answer what factors are contributive to productivity.

Guan and Chen (2012) introduce an innovated concept to further enrich the R&D performance measurement research, whereby they separate the R&D process into two stages of efficiency measures, namely knowledge production process and knowledge commercialization process. After estimating efficiency, approximating to Nasierowski and Arcelus (2003), the authors also analyze a regression model to examine the effects of environmental factors on the efficiency. Lu et al. (2014) also apply the same concept in studying the national innovation systems in 30 countries. Other relevant DEA-application studies include Zhang et al. (2003) who employ stochastic frontier analysis (SFA) to examine the R&D efficiency and productivity of firms in mainland China; Cherchye and Abeele (2005) gauge the R&D efficiency of universities in Finland and the Netherlands, respectively.

While the two-stage process model is useful, it is subject to one limitation, that is, the weights given to each stage of process model are subjective. To date, a number of studies have estimate efficiency based on a hybrid approach of DEA and

ANP (Sipahi and Timor 2010). As ANP is able to categorize and analyze complicated decision makings, a researcher may first use the technique to obtain relative weights for two or more stages of process model, which would be next used in the efficiency analysis. Furthermore, extant DEA-application studies in the R&D field may not be sufficient as they generally ignore changes in efficiency over times or dynamic performance in today's dynamic world. In summary, although several studies have been carried out to explore R&D efficiency, this study identifies a gap that should be filled.

7.3 Research Design

7.3.1 Three-Stage Value-Creation Process of R&D Organizations

Most of the existing performance evaluation studies on R&D organizations depend on efficiency specifications of R&D projects. They divide organizational efficiency into input, output, and result application and economic efficiency, which are the four major processes of R&D activities. According to the Execution Efficiency Report on Science Projects of Artificial Person Institutions, standards to evaluate the efficiencies of R&D organizations are organization development, R&D development, and industry efficiency as at the year of 2010. In line with prior studies, this study applies DEA, particularly the evaluation model created by Tone and Tsutsui (2009) to build our three-stage value-creation process of R&D organizations. Our specifications of value-creation process of R&D organizations are consistent with that of Lu et al. (2010). See Fig. 7.1 regarding the building specifications of value-creation process of R&D organizations.

In terms of the selection of input and output variables, we follow prior studies (Hsu 2005; Liu and Lu 2010; Wu et al. 2006) and base our selection on the data availability in the annual report of Execution of R&D Projects of 2009. In the stage of R&D efficiency, we examine the efficiency of R&D organizations in utilizing human resources, time and funds to generate research outputs and intellectual properties. That is, we use manpower, research time, and research funds as input variables, and patents, technology acquired, research reports, research publications, and outsourced research as output variables. In the stage of technology-diffusion efficiency, we evaluate how well research outputs and intellectual properties are disseminated. At this stage, input variables are the outputs from the stage of R&D efficiency, while output variables are patents transferred, technology transferred, technology services, and seminar. The third stage, the stage of value-creation efficiency, discusses the generation of value from the technology diffusion. The ultimate outputs include investment and production value. Table 7.1 summarizes definitions of input and output variables.

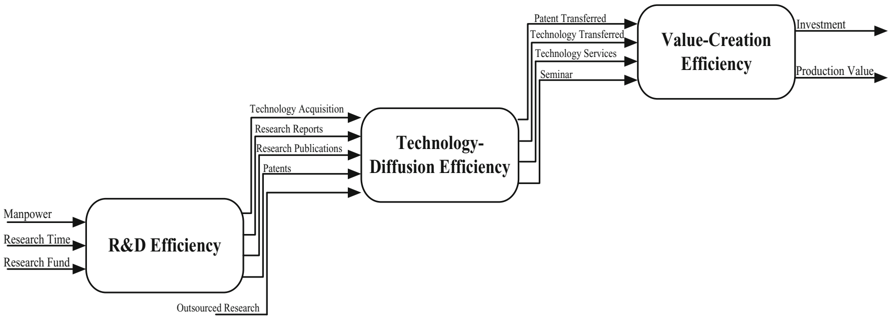

Fig. 7.1 Value-creation process of R&D organizations

Table 7.1 Definitions of the input and output variables

Item	Definition	Unit
Manpower	Manpower is the total number of personnel engaged in each project	Number
Time	Time is the total executive time of each project	Month
Budget	Budget includes all money invested in each project	Thousand
Patents	Patents are the number of patents produced by each project	Number
Technology Acquisition	Technology acquisition includes the planned, selective, focalized	Number
Research Reports	Completed the implementation of the project study report number of articles, including technical, research, training and other reports	Number
Publications	Publications include all papers and reports published by each project	Number
Sub-study	Research activities, some of the work plans by the industry or academia responsible	Number
Patent Transfer	Technology plan, through technology transfer, licensing patents to manufacturers to use the license and royalty income	Thousand
Technology Transfer	Technology and patent transfer include all technology and patent transferred to the firms by each project	Number
Technology Services	Technology services are the services provided by each project for product development, equipment calibration and maintenance, technical supports, etc., to the firms	Number
Seminar	Will result in an open manner to explain the activities of the industry, including technical seminars, training workshops, technical seminars, presentations	Number
Investment	Firm investments are the investments made by various firms for new technologies or production due to each project	Thousand
Production Value	The key results achieved through the transfer of production technology, to promote the industry to expand the production scale of the original	Thousand

Source: Definitions from the Ministry of Economic Affairs that are available in the 2009 Annual Report

7.3.2 Data Selection and Description

According to the annual reports of Execution of R&D Projects from the Department of Industrial Technology, the numbers of R&D projects executed by artificial persons are far more than industries and academics between 2005 and 2009. In other words, artificial person institutes are the major R&D power in Taiwan. We thus use 29 artificial person R&D organizations as our study objects, including eight R&D units under ITRI, six units under CSIST of Ministry of National Defense and Institute for Information Industry, Development Center for Biotechnology, Metal Industries Research & Development Center, Food Industry Research & Development Institute, Taiwan Textile Research Institute, Cycling & Health Industry R&D Center, United Ship design & Development Center, Stone & Resource Industry R&D Center, Printing Technology Research Institute, Plastics Industry Development Center, Precision Machinery Research Development Center, Medical and Pharmaceutical and Development Center, Footwear & Recreation Technology Research Institute, Animal Technology Institute Taiwan, and INER. Each R&D unit is regarded as a DMU. Furthermore, as R&D projects executed by artificial person institutes have different orientations due to their different R&D specifications, we divide the sample into two types, namely 'ordinary elements and environment establishments' and 'innovations and R&D services and compatibilities'. Note that DEA necessitates homogenous sample organizations. Therefore, we only discuss projects belong to 'ordinary elements and environment establishments'.

This study uses annual reports of Execution of R&D Projects from the Department of Industrial Technology as secondary data resource. Considering the date of publication and sources of data, we only choose samples for the period 2005–2009. These annual reports were prepared by Taiwan Institute of Economic Research (TIER), a delegate of the Department of Industrial Technology. The reports are of high credibility and completeness; they fully cover the execution results of all R&D projects run by the artificial person institutes.

The descriptive statistics of input and output variables of our research samples are shown at Table 7.2. During the sample period, the average human resource is 166 persons; the average working time is 38 months; the average of research funds is NTD404.85 millions; the average number of patents is 68; the average number of technology acquired is 20; the average number of research reports is 137; the average number of research publications is 90; the average number of research outsourced are 20; the average patent authorization fee is NTD15.75 millions; the average technology transferred is 35; the average number of technology services is 56; the average number of seminars is 22; the mean investment amount during execution time is NTD877.63 millions; the mean production value of execution time is NTD2882.34 millions. In summary, we could infer that the Taiwanese government has allocated much effort and budget in the long-term investment on R&D projects.

Table 7.3 shows the correlation coefficients among the input and output variables. The results show that the inputs and outputs are all positively and

Table 7.2 Descriptive statistics of the input and output variables

Variable	Mean	Q1	Q3	Std. dev.
Research Fund	404,851	64,302	573,850	582,475
Manpower	166	34	239	193
Research Time	38	12	48	28
Outsourced research	23	7	29	23
Investment	880,630	134,000	1,330,450	1,178,813
Production value	2,885,347	135,000	4,095,000	4,649,439
Patents	71	10	77	134
Technology acquired	4	0	5	3
Research reports	137	22	163	189
Research publications	90	16	115	132
Patent transferred	16,050	700	12,757	33,917
Technology transferred	32	11	43	33
Technology services	51	14	67	70
Seminar	25	7	29	32

significantly related, with few exceptions. It can thus be concluded that the inputs and outputs used in this study have "isotonicity" relationships. That is, the correlation analysis justifies our selection of the variables in the model (Golany and Roll 1989).

7.3.3 Dynamic Extension of Network Slack-Based Measure DEA Model

Traditional network DEA models utilize a radial measure to estimate the relative efficiency for each DMU in a multi-stage value-creation process. However, objectivity in radial models could be lacking in that they are not able to reveal the real input/output conditions for each organization, and stand on the assumption that inputs or outputs undergo proportional changes. Furthermore, the network DEA analysis is cross sectional, neglecting the efficiency changes of organizations over several periods. In this regard, we apply window analysis for the longitudinal performance measure as it is able to analyze efficiency changes across periods. Put differently, we are able to analyze the multidimensional performance of R&D organizations from a dynamic view. To overcome the shortcomings discussed above, we combine the SBM network data envelopment analysis (Tone and Tsutsui 2009) and the window analysis (Klopp 1985) to ensure enhanced estimates of efficiency across periods with internal linking activities in a single implementation for every DMU.

This study deals with n R&D organizations ($j = 1, \ldots, n$) consisting of K stages ($k = 1, \ldots, K$) in T periods ($t = 1, \ldots, T$); m_k and r_k are the numbers of inputs and outputs to stage k, respectively; $z_{dj}^{t(f,h)}$ is the amount of linking intermediate product

Table 7.3 Correlation coefficients among the input and output variables

	x_1	x_2	x_3	z_1	z_2	z_3	z_4	z_5	y_1	y_2	y_3	y_4	u_1	u_2
Manpower (x_1)	1													
Research Time (x_2)	0.270**	1												
Research Fund (x_3)	0.974**	0.185*	1											
Patents (z_1)	0.922**	0.089	0.964**	1										
Technology Acquired (z_2)	0.593**	0.206*	0.591**	0.548**	1									
Research Reports (z_3)	0.950**	0.216**	0.935**	0.887**	0.650**	1								
Research Publications (z_4)	0.946**	0.136	0.953**	0.943**	0.589**	0.908**	1							
Outsourced Research (z_5)	0.768**	0.180*	0.732**	0.684**	0.570**	0.730**	0.762**	1						
Patent Transferred (y_1)	0.413**	0.469**	0.404**	0.427**	0.114	0.303**	0.312**	0.105	1					
Technology Transferred (y_2)	0.405**	0.505**	0.350**	0.304**	0.433**	0.383**	0.401**	0.431**	0.238**	1				
Technology Services (y_3)	0.481**	0.278**	0.467**	0.416**	0.355**	0.457**	0.495**	0.293**	0.170*	0.332**	1			
Seminar (y_4)	0.822**	0.064	0.852**	0.831**	0.576**	0.831**	0.865**	0.762**	0.220**	0.350**	0.367**	1		
Investment (u_1)	0.446**	0.574**	0.352**	0.281**	0.198*	0.399**	0.357**	0.427**	0.415**	0.656**	0.238**	0.364**	1	
Production value (u_2)	0.291**	0.476**	0.196*	0.151	0.092	0.206*	0.226**	0.288**	0.404**	0.382**	0.146	0.140	0.617**	1

Note: ***P < 0.01; **P < 0.05; *P < 0.1

d from stage f to stage h to organization j in period t; The window starting at time t, $1 \leq t \leq T$ and with the width w, $1 \leq w \leq T - t$, has $n \times w$ observations. $T - w + 1$ is the number of windows ($p = 1, \ldots, T - w + 1$). The dynamic extensions of network SBM DEA model for the observed organization in period t with the width w under a variable returns to scale assumption and the free link activities program problem is as follows:

$$\eta_o^p = Min \frac{\sum_{k=1}^{K} \omega_k \sum_{p=1}^{T-w+1} \left[1 - \frac{1}{m_k} \left(\sum_{i=1}^{m_k} \frac{s_i^{p,k^-}}{x_{io}^{p,k}} \right) \right]}{\sum_{k=1}^{K} \omega_k \sum_{p=1}^{T-w+1} \left[1 + \frac{1}{r_k} \left(\sum_{r=1}^{r_k} \frac{s_r^{p,k^+}}{y_{ro}^{p,k}} \right) \right]}$$

$$\begin{aligned}
& S.T. \\
& x_{io}^{p,k} = \sum_{p=1}^{T-w+1} \sum_{j=1}^{n \times w} x_{ij}^{p,k} \lambda_j^{p,k} + s_i^{p,k^-}, \quad i = 1, \ldots, m_k,\ p = 1, \ldots T - w + 1, \\
& y_{ro}^{p,k} = \sum_{p=1}^{T-w+1} \sum_{j=1}^{n \times w} y_{rj}^{p,k} \lambda_j^{p,k} - s_r^{p,k^+}, \quad r = 1, \ldots, r_k,\ p = 1, \ldots, T - w + 1, \\
& \quad \sum_{p=1}^{T-w+1} \sum_{j=1}^{n \times w} z_{dj}^{(f,h)} \lambda_j^{p,h} = \sum_{p=t}^{t=w-1} \sum_{j=1}^{n} z_{dj}^{(f,h)} \lambda_j^{p,f},\ \forall (f,h), \\
& \quad \sum_{p=1}^{T-w+1} \sum_{j=1}^{n \times w} \lambda_j^{p,k} = 1, \quad k = 1, \ldots, K,\ p = 1, \ldots, T - w + 1, \\
& \quad \lambda_j^{p,k} \geq 0,\ s_i^{p,k^-} \geq 0,\ s_r^{p,k^+} \geq 0;\ j = 1, \ldots, nw,
\end{aligned} \tag{7.1}$$

where s_i^{p,k^-} and s_r^{p,k^+} are the optimal input slacks and output slacks at stage k; ω_k is the relative weight of stage k which is determined corresponding to its importance and $\sum_{i=1}^{k} \omega_k = 1, \omega_k \geq 0 (\forall k)$. $\sum_{p=1}^{T-w+1} \sum_{j=1}^{n \times w} \lambda_j^{p,k} = 1$ constructed best practice frontier exhibits variable returns to scale technology at stage k with window p. Transforming this program problem into a linear program using the Charnes and Cooper transformation (Charnes et al. 1978) will solve the problem itself.

If $\eta_o^{p^*} = 1$ in (7.1), the observed organization is called overall efficient in window p. The efficiency of observed organization at stage k in window p can be defined by

$$\tau_{ko}^{p*} = \frac{\sum_{p=1}^{T-w+1} \left[1 - \frac{1}{m_k} \left(\sum_{i=1}^{m_k} \frac{s_i^{p,k^{-*}}}{x_{io}^{p,k}} \right) \right]}{\sum_{p=1}^{T-w+1} \left[1 + \frac{1}{r_k} \left(\sum_{r=1}^{r_k} \frac{s_r^{p,k^{+*}}}{y_{ro}^{p,k}} \right) \right]}, \quad k = 1, \ldots, K, \tag{7.2}$$

$$p = 1, \ldots, T - w + 1,$$

where $s_i^{p,k^{-*}}$ and $s_r^{p,k^{+*}}$ are the optimal input slacks and output slacks in (7.1). If $\tau_{ko}^{p*} = 1$, then the observed organization is technically efficient at stage k. If τ_{ko}^{p*} is smaller than one, then the observed organization is technically inefficient.

7.4 Results and Discussions

7.4.1 Performance Analysis in Value-Creation Process

Many researchers have utilized the ANP techniques for multi-criteria decision analyses (Sipahi and Timor 2010) as this method is particularly useful in analyzing complicated decisions. In this study, three stages of efficiencies are developed to comprehensively measure the dynamic performance of R&D organizations in Taiwan. Using ANP, we are able to find the relative importance of each stage of the value-creation process. Specifically, five R&D managers are randomly chosen from the sample R&D organizations and asked to evaluate the relative importance of value-creation process based on the first evaluation part of ANP by Saaty (1996). Table 7.4 shows the results of the weights obtained for each stage of the value-creation process. The relative weights in Table 7.4 are calculated as follows. First, we ask the five managers to express their viewpoints on the relative importance of each stage through the Likert Scale of 1–9 as in Saaty (1996). With that, the relative weights are obtained accordingly. Second, we calculated the geometric mean of the scores obtained in the first step. These mean values are used as the input weights for the efficiency estimates of the value-creation process.

For understanding the connectivity of inner economical activities of R&D organizations over long-term periods, we integrate window analysis and network DEA to evaluate the R&D efficiency, technology-diffusion efficiency, and value creation efficiency of Taiwanese R&D organizations for the period 2005–2009. In order to understand dynamic performance of these 5 years, we calculate a 5-year average performance value of each R&D organization. We also use standard deviation to determine the stability of the 5-year performance.

Table 7.4 Input weights for value-creation process

Expert	R&D efficiency	Technology-diffusion efficiency	Value-creation efficiency	Sum
Manager 1	0.467	0.256	0.277	1.000
Manager 2	0.415	0.342	0.243	1.000
Manager 3	0.473	0.243	0.284	1.000
Manager 4	0.513	0.212	0.275	1.000
Manager 5	0.455	0.282	0.263	1.000
Mean	0.465	0.265	0.270	1.000

Dynamic performance of each stage is shown in Table 7.5. For R&D efficiency, the overall average efficiency score is 0.459. There are five R&D organizations that achieve an efficiency value of at least 0.8, namely SRIRDC, PTRI, PIDC, FRTRI, and INER. We further check the standard deviations of the five organizations; the results show that their variation levels are generally and relatively smaller than those of other organizations, implying that their performance is more stable as compared to others over the sample period. The top-performing R&D organization is PTRI, which has the highest R&D efficiency score and the lowest value of standard deviation. This finding means that this organization is the best learning benchmark for other R&D organizations.

To remove the R&D inefficiency, we suggest that the R&D organizations should apply patent for valuable key technologies, design global patent map, and increase creation of intellectual properties. In terms of technology acquisition, the organizations should reinforce international cooperation and technology authorization, so that their R&D level could improve and reach international level. More importantly, they are able to possess their core technologies. As for research reports and research publications, the organizations should work harder on preparing technical reports and publishing academic studies to show their achievement in R&D and accomplishment in academic research. In summary, the R&D organizations should focus on key profitable technology, patent map layout, intellectual property, and academic achievement.

On the front of technology-diffusion efficiency, the overall average efficiency score is 0.608. There are 11 organizations that achieve an efficiency value of at least 0.8. We further check their standard deviations, which shows that the results of these organizations are again better than those of others. Among the organizations, two organizations, APIT and INER, are considered as efficient in terms of technology-diffusion efficiency. Therefore, other organizations should take the two organizations as the best learning model for diffusing technology.

Our suggestions for organizations that need improvement in terms of technology-diffusion efficiency are as follows. First, organizations should actively transfer their research results to industries and increase their profit from patent authorization fees (technology transfer and patent authorization); organizations should hold technology forums, training camps, and exhibitions to present their research reports with the purpose of helping industries to enhance their technology capabilities (seminars). To accelerate the technological development in the industries, R&D organizations should fully utilize technology services, international standard authentications, and technology platform exchange mechanisms to provide technical help to industries in R&D activities (technology and industry services). In summary, R&D organizations should enforce the proliferation effect of their R&D results, and establish transfer mechanisms of technologies, patents, and industry services.

As for the results on the value-creation efficiency, the overall average efficiency value is 0.176. There is only one R&D organization with an efficiency value above 0.8, viz. ITRI_CCRL. For this stage, we also provide some suggestions for improvement. First, R&D organizations should actively transfer their research

Table 7.5 Mean efficiencies of R&D organizations for the 3-year windows during 2005–2009

R&D organizations	R&D efficiency		Technology-diffusion efficiency		Value-creation efficiency		Overall efficiency	
	Mean	Std. dev.	Mean	Std. dev.	Mean	Std. dev.	Mean	Std. dev.
ITRI_HQ	0.320	0.140	0.188	0.025	0.050	0.047	0.212	0.062
ITRI_EORL	0.149	0.024	0.645	0.225	0.090	0.088	0.265	0.054
ITRI_CCRL	0.192	0.060	0.466	0.208	0.806	0.290	0.431	0.036
ITRI_MSRL	0.246	0.309	0.373	0.353	0.473	0.296	0.341	0.315
ITRI_MCRL	0.254	0.177	0.485	0.165	0.566	0.327	0.399	0.132
ITRI_EERL	0.318	0.082	0.657	0.242	0.195	0.119	0.375	0.087
ITRI_BERL	0.271	0.034	0.425	0.115	0.018	0.024	0.243	0.047
ITRI_STC	0.415	0.076	0.610	0.233	0.137	0.158	0.392	0.084
Mean	0.271	0.059	0.481	0.109	0.292	0.073	0.332	0.064
CSIST_RL1	0.601	0.256	0.550	0.209	0.034	0.027	0.434	0.166
CSIST_RL2	0.395	0.103	0.521	0.273	0.035	0.021	0.331	0.110
CSIST_ERL	0.338	0.122	0.527	0.227	0.096	0.049	0.323	0.102
CSIST_CTI	0.222	0.036	0.177	0.046	0.154	0.061	0.192	0.021
CSIST-RL4	0.407	0.031	0.536	0.172	0.124	0.112	0.365	0.057
CSIST-RL5	0.179	0.024	0.187	0.010	0.450	0.312	0.254	0.096
Mean	0.357	0.048	0.416	0.078	0.149	0.068	0.316	0.044
III	0.162	0.109	0.155	0.047	0.432	0.178	0.233	0.098
DCB	0.257	0.063	0.926	0.166	0.216	0.439	0.423	0.069
MIRDC	0.212	0.082	0.280	0.117	0.370	0.120	0.273	0.058
FIRDI	0.272	0.035	0.766	0.226	0.122	0.080	0.363	0.067
TTRI	0.192	0.016	0.233	0.026	0.208	0.089	0.207	0.020
CHIRDC	0.661	0.132	0.787	0.147	0.048	0.035	0.529	0.077
USDDC	0.655	0.021	0.584	0.159	0.080	0.031	0.481	0.048
SRIRDC	0.875	0.151	0.975	0.056	0.032	0.012	0.674	0.064
PTRI	1.000	0.001	0.976	0.053	0.228	0.432	0.785	0.121
PIDC	0.938	0.082	0.864	0.304	0.071	0.076	0.684	0.109
PMRDC	0.635	0.061	0.939	0.076	0.023	0.014	0.550	0.025
MPDC	0.607	0.173	0.874	0.117	0.009	0.016	0.516	0.112
FRTRI	0.889	0.168	0.932	0.069	0.019	0.014	0.666	0.061
APIT	0.717	0.076	1.000	0.000	0.019	0.034	0.604	0.039
INER	0.921	0.033	1.000	0.000	0.005	0.006	0.695	0.017
Mean	0.600	0.026	0.753	0.033	0.125	0.046	0.512	0.014
Total average	0.459	0.028	0.608	0.042	0.176	0.033	0.422	0.024

results to the industries, get their patents authorized, and utilize delegations and industry services. This is because through the proliferation of their technology results to value-added applications in the industries, they are able to fully bring positive effects from direct and indirect investments, such as an increase in the production value, newly created industries. In summary, R&D organizations have to concern about increasing the values of the industries, creating new profit basis for the industries, and growing Taiwanese companies from ‘technology followers’ to ‘value creators’.

From the above-discussed results, we find that the average efficiency score of the technology-diffusion efficiency (0.608) is better than that of the R&D efficiency (0.459) and the value-creation efficiency (0.176). The findings suggest that R&D organizations should (i) enforce the proliferation effect at the stage of technology-diffusion efficiency, (ii) transfer their technologies and timely get their patents authorized, and (iii) disseminate their research results through the technology services and consultancy services.

7.4.2 The Relationship Between Capital Stock and R&D Organizations Performance

The purpose of establishing R&D organizations is to raise the technology level of the industries and to accelerate the innovation in the industries, which could create values. As a result, it is important that R&D organizations invest in the capital stock of patents. Currently, a patent in Taiwan will be protected by law for 10 years; the economical benefits of research outcomes are also protected by patent law for up to a maximum of a decade. In other words, a researcher should evaluate patents from the perspective of the capital stock of patents.

This study uses the number of patents as the proxy of the capital stock of patents, consistent with prior studies that also use the number of patents to gauge the capability of R&D and innovation (Griliches 2007; Hall and Bagchi-Sen 2007; Trajtenberg 1990). It has been argued that the more patents a R&D organization has, the stronger its power is at technological development and innovation (Griliches 2007; Trajtenberg 1990). In measuring the capital stock of patents, a researcher can amortize the capital stock of patents of a R&D organization at 15 %. Specifically, the formula to calculate the capital stock of patents (*PAT*) for *i* R&D unit at year *t* is as follows:

$$PAT_{i,t} = PAT_{i,t-1} \times (1 - 15\,\%) + P_{\mathrm{t}} \tag{7.3}$$

where *P* is the ratio of the number of patents acquired to the number of patents applied of each R&D organization (the patent acquired ratio).

In addition to the capital stock of patents, prior studies also indicate that the quality of human resources and capability of service support could affect the performance of a R&D organization. The quality of human resources can be evaluated by their education and working experiences (Souitaris 2002). Therefore, we define the quality of human resources as the number of employees with doctoral degrees in a R&D organization because better qualified human resources would possess higher quality of research capability. In other words, talented employees are the cornerstone of technological development and innovation, as well as the core of knowledge-based economic development. Consistent with Souitaris (2002) who finds that the quality of R&D human resources are highly related to technical innovation, we predic that the quality of R&D human resources is positively related to the performance of R&D organizations.

In implementing R&D projects or developing new products, R&D organizations use their existing technologies and equipments to provide short-term services such as maintenance and technical consultancy. In this study, we use the average charged amount of contracted service for the industries to proxy for the capability of service support. A higher value of the variable indicates that an organization has better capability at providing service support. Specifically, R&D organizations are able to provide better services to their customers through innovating their services (Chakravarty et al. 1995; Upton 1995) because the capability of service support is the key element in achieving competitive advantage. Therefore, we predict that there is a positive relationship between the capability of service support and the performance of R&D organizations.

To determine the relationship between the capital stock of patents, quality of human resources, and capability of service support, and the performance of R&D organizations, we apply panel data regression models. Banker and Natarajan (2008) have documented that the use of a two-stage procedure involving DEA followed by an ordinary least squares (OLS) regression analysis yields consistent estimators of the regression coefficients. Note that panel data estimation procedures are superior to the simply-pooled OLS procedures. An advantage of panel data regression is that it could adjust for organization-specific and year-specific effects.

Table 7.6 presents the panel data regression. The results show that the capital stock of patents is positively and significantly related to the R&D efficiency and technology-diffusion efficiency. Although the capital stock of patents is negatively related to the value-creation efficiency, the coefficient doesn't reach the conventional significance level. In the technological development and innovation process, patents are the key to performance. That is, the number of patents acquired reflects the degree of competitiveness of a R&D organization (Deeds and Hill 1996; Mowery et al. 1996). As noted earlier, we study patents acquired by the R&D projects that are executed by 29 artificial person institutes for the period 2005–2009. The untabulated statistics show that approximately 6000 units of patents were acquired by these organizations. While the results imply that the R&D organizations have been planning their global patent policies, building complete lines of patents, enforcing the quality of patents, and generating competitive advantages of their research results, the negative association between the capital stock of patents and value-creation efficiency indicates that R&D organizations should continue (i) to introduce new and advanced technologies, (ii) to learn higher level key technologies, and (iii) to integrate superior resources in the organizations. These methods could ensure that the R&D organizations are able to demonstrate their capabilities at design, production and management, to build up their irreplaceable specialization, and ultimately create values through competitive advantages.

Table 7.6 Results of panel data regression

	Dependent variable		
	R&D efficiency	Technology-diffusion efficiency	Value-creation efficiency
Independent variables	Fixed-effect model	Random-effect model	Random-effect model
Constant		0.400	0.201
Patent capital stock	0.352*	0.778***	−0.111
Quality of HR	0.145	0.220	−0.461
Ability of service support	0.297***	0.190*	0.788
R^2	0.640	0.311	0.536

Note: ***P < 0.01; **P < 0.05; *P < 0.1

However, the regression results in Table 7.6 show that there is no significant relationship between the quality of human resources and the performance of R&D organizations. A R&D organization should be able to create future competitiveness by acquiring new technical knowledge, developing new technologies through cooperation with other countries, exchanging knowledge and personnel with foreign institutes, and transforming human resources into value. That is, it might mean that R&D organizations concentrate too much on their capabilities of R&D but pay less attention the important roles played of their employees.

As for the capability of service support, the coefficients are all positive, but only those for the R&D and technology-diffusion efficiencies are significant. These outcomes support our prediction that the better the capability of service support, the better the performance of R&D organizations, suggesting that customers are satisfied if organizations can provide valuable service support. During the sample period, the accumulated number of industry services cases reached 6911 and the revenue was NTD8000 millions, which means that R&D organizations actively deploy their core technologies and help the industries to raise their values.

7.5 Conclusions

In today's dynamic economic environment, evaluating the performance of R&D organizations is a process that requires a comprehensive measure to characterize it. In this study, we develop a dynamic three-stage network DEA model through the combination of window analysis and network DEA. The innovative DEA model evaluates the R&D efficiency, technology-diffusion efficiency, and value-creation efficiency of Taiwanese R&D organizations over the period 2005–2009. Before performing DEA analysis, we first apply the ANP technique to define the relative importance of each stage of efficiency. The DEA analysis suggests that managers should first focus on removing the technology-diffusion inefficiency, then eliminating the value-creation inefficiency, and finally improving the R&D efficiency.

In the second stage, panel data regression is employed to examine the impacts of the capital stock of patents, quality of human resources, and capability of service support on the dynamic performance of the R&D organizations. The panel data regression outcomes shows that the capital stock of patents and capability of service support positively affect the performance of R&D organizations.

Despite the innovative application of the dynamic and network DEA models in this study, we highlight that future studies may apply the dynamic network SBM model by Tone and Tsutsui (2014) to account for dynamic efficiencies. Note that, however, this study looks at R&D organizations that can hardly be characterized by carry-overs, which are permanent accounts that are accumulated over periods, used in the dynamic SBM model. Therefore, future research may apply the similar innovative approach to examine organizations in a different industry or even the dynamic network SBM model for the same industry when more data become available to the public.

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