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An actor-network perspective on evaluating the R&D linking efficiency of innovation ecosystems

Ping-Chuan Chen [a], Shiu-Wan Hung [b,*]

[a] Executive Master Program of Business Administration in Biotechnology, Taipei Medical University, Taipei 110, Taiwan
[b] Department of Business Administration National Central University, 320, Taiwan

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ABSTRACT

Research and development (R&D) is one of the key factors contributing to the economic growths in both advanced and developing countries. Implementing technological innovation strategies to accelerate the research and development has thus become one of the most important industrial policies for governments. The R&D performance is highly influenced by the complexities of interactions among actors in an innovation system. An evaluation model that incorporates the influence of linking activities is highly desired. This study employed the actor-network theory to construct a three-stage R&D production framework that emphasizes the linking activities among basic research stage, technology translation stage, and system development stage. In addition, the network data envelopment analysis (DEA) method was used to evaluate the relative R&D efficiency across the global twenty-five countries. The analysis results screened out specialized efficient country at each sub-process and further constructed the efficiency group for benchmark-learning. This study also pointed to the importance of the research institution for technology commercialization. The potential application of network DEA and actor-network theory approach in assessing the efficiency of R&D activities were also highlighted.

1. Introduction

Research and development (R&D) have become key factors contributing to economic growth in both advanced and developing economies (Corrado et al., 2009; Falk, 2006; Mario, 2009; OECD, 2007; Schwab, 2012). The increase in a country's overall level of R&D efficiency leads to the corresponding increases in its competitive advantage (De Jorge and Suarez, 2011; Kang and Park, 2012; Sosa, 2012). Implementing technological innovation strategies to accelerate the research and development has thus become one of the most important industrial policies for governments. For example, the National Science and Technology Council of United States have been developing national strategic plan for advanced manufacturing to guide the federal program and activities in support of the research and development (Holdren, 2012). The council considered that the acceleration of innovation required the bridging of a number of gaps in the present innovation system, particularly the gap between R&D activities and the development of technological innovations in domestic production of goods. To achieve optimal effects, the decision-making and strategic planning of R&D investment needs to be well coordinated in evaluating the relative efficiency of the innovation system. However, the operation of innovation system is a multi-dimensional network and interconnected by actors in different organizational context (e.g. university, government and non-profit research institutions, and business enterprises). The complexities of innovation outcomes are strongly influenced by the interactions among actors in the innovation system (network) (Hoholm and Araujo, 2011). Despite previous researches have investigated the R&D performances, they neglected the existence and interacting effects of internal or linking activities, and thus could not evaluate the impact of sector-specific inefficiencies on the overall efficiency of the system as a whole (Färe and Grosskopf, 2000; Lewis and Sexton, 2004; Löthgren and Tambouur, 1999; Prieto and Zofío, 2007). Therefore, an evaluation model that takes into account the effects of actors' co-linking activities in the innovation process is highly desired.

The actor-network theory, proposed by researchers from the sociology of science (Latour, 1987; Callon, 1986; Law, 1992; Bijker and Law, 1992), examines the motivations of actors who form the elements, linked by association, of heterogeneous networks of aligned interests (Walsham and Sahay, 1999). The philosophy of actor-network theory has become widely acknowledged in recent years, particularly in the field of innovation research (Alcouffe et al., 2008; Donaldson et al., 2002; du Preez, 2012; Hoholm and Araujo, 2011; Miettinen, 1999; Prout, 2008; Remírez et al., 2011; Thrane et al., 2010; Yoo et al., 2005), and organizational studies and strategic management (Czarniawska, 2006; Durepos and Mills, 2012; Lagesen, 2012; Steen, 2010; Vickers and Fox, 2010; Whittle and Spicer, 2008). This study employed the

* Corresponding author at: Department of Business Administration National Central University, No. 300, Jung-Da Road, Jung-Li city, Tao-Yuan 320, Taiwan.
E-mail address: shiuwan@mgt.ncu.edu.tw (S.-W. Hung).

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actor-network theory to illustrate how the dynamic mechanism of innovation emerges and unfolds at the national level in practice.

According to the literature, the innovation processes are highly situated and contingent (Pavitt, 2005) with linkages among actors, organization, industrial network and other distant sectors. The national innovation system is a set of interacting actors (e.g. university, government and non-profit research institutions, and business enterprises) that create scientific knowledge. All actors in the innovation system need to collaborate in formal and informal networks not only to generate new knowledge but also to strategically create and shape supportive system resources. Cohen and Levinthal (1989) proposed that the purposeful establishment of selective interactions within networks can promote firms to access complementary knowledge. Griliches (1979) demonstrated that the generation of knowledge may be viewed as the outcome of a knowledge production process. The production of new knowledge requires the access to external knowledge as a source of new ideas either to improve existing technologies or to provide the basis for brand new ones. Previous studies have highlighted the effect of knowledge spillovers on the total factor productivity (TFP) growth (Dumais et al., 2002; Jones, 1995; Krammer, 2015; Romer, 1990; Thompson, 2006). Romer (1990), Jones (1995) and others adopted the endogenous growth model of profit-seeking firms' investments in R&D and demonstrated that the firm's R&D not only raises its profits, but also has a positive externality on other firms' R&D productivity. Although the importance of externalities in knowledge or R&D had been recognized, there is an ongoing debate as to what extent knowledge spillovers can actually increase long-term per capita growth (Gehringer, 2016; Jones, 1995; Romer, 1990). These knowledge creation and transfer processes are, however, characterized by uncertainty and controversy, particularly in the interactions among actors in the network and the exploration of knowledge. Antonelli et al. (2011) indicated that the intentional interactions among innovative agents are important to the success of knowledge production processes. Since the R&D performance of the innovation system is a complex phenomenon situated within a network of interconnected processes, the linkages in the network should tighten the institutionally embedded relationship between innovation production and environment (Guan and Chen, 2012; Hoholm and Araujo, 2011). This study aimed to re-construct the innovation system from the actor-network theory perspective and further examine the relative R&D efficiency from a multi-dimensional viewpoint.

The study proposed a three-stage R&D production framework, including the basic research stage, the technology translation stage, and the system development stage, to analyze the R&D performance of different countries. The linking activities among actors were considered (Levinthal and Myatt, 1994; Nelson, 1995). By using the network data envelopment analysis (DEA) method, this study evaluated three-stage performance models, namely, research efficiency, translation efficiency and economic efficiency. Since its introduction in late 1970s, data envelopment analysis (DEA) has been a popular method for measuring the relative efficiency of decision-making units (DMUs) with multiple inputs and outputs (Charnes et al., 1978). DEA is a linear programming based technique that converts multiple input and output measures into a single comprehensive measure of performance. The application of DEA is strongly supported in the multitude of empirical analyses methods which inherently regards tradeoffs among various quantity measures for evaluating the relative R&D efficiency at the firm, industry and national levels (Garcia-Valderrama et al., 2009; Guan and Chen, 2012; Hashimoto and Haneda, 2008; Kumbhakar et al., 2012; Lu and Hung, 2011; Sharma, 2012; Sharma and Thomas, 2008).

This study regarded R&D generation activity as a production process, and considered each country as a decision-making unit (DMU) which conducts R&D activities within the innovation system. By employing the actor-network theory, this study offered an alternative perspective and characterization of the divisional efficiencies of the innovation system via a three-stage process that emphasizes the effect of linking activities. We "followed the actor" (Latour, 1987) where the R&D production happened to unfold in each different actor-network, and set up three different R&D production stages, including developing novel ideas into scientific knowledge by academia during the basic research stage, transforming the scientific knowledge into industrial practice by research institute during the technology translation stage, and implementing the innovation into economic outcome and commercializing by business enterprises during the system development stage. In addition, the linking activities among actors were also considered in the study, including joint research, technology transfer, and university-industry collaboration. By constructing an inter-country R&D production framework, the actor-network theory approach of this study could be used to identify the transformation of innovation context in which actors get involved.

This paper is organized as follows. An overview of R&D performance evaluation and actor-network theory is given in Section 2. In Section 3, we present the conceptual performance model of actor-network innovation system. The data selection and research methodology are also addressed in Section 3. Section 4 presents the empirical results and discussion. Finally, Section 5 concludes with the finding of this study and provides implications for policy makers with insight into resource allocation and strategic decision-making.

2. Literature review

2.1. R&D performance evaluation

Various literatures devoted to the investigation of R&D performance at the firm and industry levels. Kumbhakar et al. (2012) applied the stochastic frontier analysis approach to examine the impact of corporate R&D activities on firm performance, comprised of top European R&D investors over the period 2000–2005. De Jorge and Suarez (2011) provided evidence of the effects of subsidies for R&D activities on technical efficiency from Spanish manufacturers during the period 1993–2002. Zhang et al. (2003) investigated the influence of ownership on the R&D efficiency of Chinese firms. Moreover, several other studies also examined R&D performance at the industry level (Gonzalez and Gascon, 2004; Hartmann, 2003; Hashimoto and Haneda, 2008; Meliciani, 2000; Sharma, 2012). Sharma (2012) investigated the impact of R&D activities on firm performance of the Indian pharmaceutical industry. Hashimoto and Haneda (2008) used the data envelopment analysis (DEA) and Malmquist index method for measuring the change in R&D efficiency at both firm and industrial levels. In addition, Gonzalez and Gascon (2004) analyzed the evolution of the productive patterns in a sample of 80 pharmaceutical laboratories that operated in Spain from 1994 to 2000. Meliciani (2000) examined the effect of research and investment activities on patents across industries.

Meanwhile, other studies have investigated the relative efficiency of R&D performance across countries (Guan and Chen, 2012; Lu and Hung, 2011; Pan et al., 2010; Garcia-Valderrama et al., 2009; Lee et al., 2009; Sharma and Thomas, 2008). Guan and Chen (2012) emphasized the effects of policy-based institutional environment on the relative efficiency of various innovation systems. Pan et al. (2010) reconciled diverse efficiency measures to characterize the operating performance of the national innovation system across countries. Lee et al. (2009) evaluated the national R&D programs focusing on R&D policy and resource allocation. Lu and Hung (2011) also pointed to the importance of intellectual capital in achieving high level of efficiency of national technology development program. Sharma and Thomas (2008) explored the inter-country R&D efficiency using the DEA approach and highlighted the inefficiency in the R&D resource usage.

Most of these studies used the factors of manpower, R&D expenditures, publications and patents for evaluating the effects of the R&D investment at the firm, industrial and national levels. Furthermore, despite various studies had used the DEA method which inherently regards tradeoffs among various quantity measures for evaluating the relative R&D efficiency, most researchers neglected the influence of the actor-network relationship on the R&D performance. An evaluation model that takes into account the effects of co-linking activities of each actor in the innovation process is highly desired (Hoholm and Araujo, 2011). In addition, although many countries invested large amount of resources on R&D, these resources may not be not used effectively. Additional investment on the academia institutions is of little use in stimulating scientific progresses. Hence, how to utilize the national R&D investment and allocate the resource has become the main concern of the policy makers for all countries. This study aimed to re-construct the innovation system from the actor-network theory perspective and further examine the relative R&D efficiency from a multi-dimensional perspective.

2.2. Actor-network theory

The actor-network theory was first proposed by researchers from sociology of science to explore the knowledge production by ethnographic studies of scientific laboratories (Bijker and Law, 1992; Bijker et al., 1987; Knorr Cetina, 1981; Latour, 1996; Latour and Woolgar, 1979). The initial application of the actor-network theory was pioneered at the Ecole des Mines in Paris, with the need for a new social theory adjusted to science and technology studies. Later, Callon (1986) analyzed the application of science to scallop fishing in northern France, and explained how scientists persuade a group of fishermen of the utility of scientific knowledge. Latour (1987) documented how scientific facts are established in the laboratories, and tended to generalize the construction of networks. Along with Callon (1986), Latour (1987), and Law (1992) further explained the metaphor of heterogeneous network and discussed the strategies of network ordering. Actor-network theory is an interdisciplinary approach that explains how technology can facilitate the organizational activities and tasks performed. Since 1990s, the actor-network theory became as a popular tool for analysis in the fields of science, technology, and society. The theory was also picked up and developed by researchers in parts of organizational analysis, informatics, health studies, geography, sociology, anthropology, feminist studies and economics (Miettinen, 1999; Donaldson et al., 2002; Yoo et al., 2005; Czarniawska, 2006; Whittle and Spicer, 2008; Prout, 2008; Alcouffe et al., 2008; Thrane et al., 2010; Steen, 2010; Vickers and Fox, 2010; Remírez et al., 2011; du Preez, 2012; Durepos and Mills, 2012; Lagesen, 2012).

The actor-network theory has sought to emphasize the continuity and fall of social networks, in viewing the network as heterogeneous. By the emerging perspectives on science and technology as relationally constructed by the social practice (Latour, 1987; Callon, 1986; Law, 1992; Bijker and Law, 1992), the actors include not only humans, but also technology, texts, symbol and other artifacts as actors, which can participate in these social relationships. Latour (1996) further indicated that actors can be technical artifacts ranging from smallest components to the largest, and argued these actors are defined solely by their ties to other actors. Hence, these actors could build their own network by making the other actors dependent upon their knowledge and align with their interests. The building of an actor network is to overcome the resistance of other actors and try to weave them into network with other actors (Law, 1992). Through the enrollment of a sufficient body of allies and the translation of their interests, the actors are willing to participate in particular ways of acting that maintain the network (Walsham and Sahay, 1999). Thus, the perspective of actor-network theory can provide a conceptual framework to help understand the development of open-ended socio-technical system and strategies by aligning the interests of the actor-network.

The core concept of actor-network theory lies in the different processes of translation. Each actor has his/her/its own view of the network, and seeks to align their interests with the network. Callon (1986) considered the extension of science as exercising of power relations, and indicated that both actors and actants share in the reconstruction of the network of interaction leading to system stabilization through the processes of problematisation, interessement, enrollment, and mobilization of allies. While the focus of Callon's study is on the world of the scientists involved in network building, Wynne (1992) argued that enrolled actors may experience a fundamental ambivalence toward scientific knowledge, and particularly indicated the conflicts between scientists and local knowledge. Moreover, Clark and Murdoch (1997) modified Callon and Wynne's perspectives with the socio-spatial context to help understand the actor-networks.

The contribution of actor-network theory on knowledge production is well accepted; exactly how the knowledge and technology developed and commercialized over time has been also explored in the knowledge-based industry (Bengtsson and Ågerfalk, 2011; Cresswell et al., 2010; Doolin and Lowe, 2002; Greenhalgh and Stones, 2010; Papadopoulos et al., 2011; Yoo et al., 2005). However, previous studies do not explain how the innovation evolves in practices clearly (Gupta et al., 2007; Van de Ven et al., 1999). In addition, little is known about how the actors draw the boundaries and frame their activities in the different contexts. The integrated understanding of different actor-networks based on the socio-spatial context is important. This study aimed to provide such information.

3. Research design

3.1. Three-stage transformation model of actor-network innovation system

Previous researches reported that the flows of technology and information among people, companies and institutions are crucial to the innovative process (Fagerberg and Sapprasert, 2011; Freeman, 1987; Lundvall, 2007; Nelson and Nelson, 2002; Pavitt, 1999). At national level, innovation and technology development are the results of a complex set of linkages among actors producing, distributing and applying different types of knowledge. These actors are primarily universities, research institutes, business enterprise, and the people within them. The conceptual framework of this research is shown in Fig. 1, which is consisted of a three-stage transformation of the actor-network innovation system.

This study proposed the three different R&D production stages, namely the basic research stage, technology translation stage, and system development stage. The basic research is a systematic study directed toward greater knowledge or understanding of the fundamental aspects of phenomena and of observable facts. The actor-network at the basic research stage is carried out by the academia sector, while the research findings may provide some guidelines to solve the specific industrial problems (Rosenberg, 1990). The technology translation aims to develop a model of knowledge transfer and migration, which is derived through discussions with experienced intermediaries from the universities and industrial specialists involved in knowledge transfer. While the actor-network at the technology translation stage is completed by the research institution sector, the technology translation could bridge the gaps between the industry and the knowledge base of universities (Iles and Yolles, 2002). On the other hand, the systems development aims to produce high quality systems that meet customer requirements within scheduled time-frames and cost estimates, and the actor-network at the systems development stage is carried out by the industry sector. According to Taylor (2003), the systems development life cycle focuses on realizing the product requirements. The linking activities investigated include the complexities of interactions among actors in the ecosystem. For example, the linkages between university and research institution can take the form of joint research, publications, and research personnel exchanges. The interactions between university and industry sector are usually industry-university cooperative research project and cultivation of talent. Besides, there are related industrial collaboration between research institution and industry

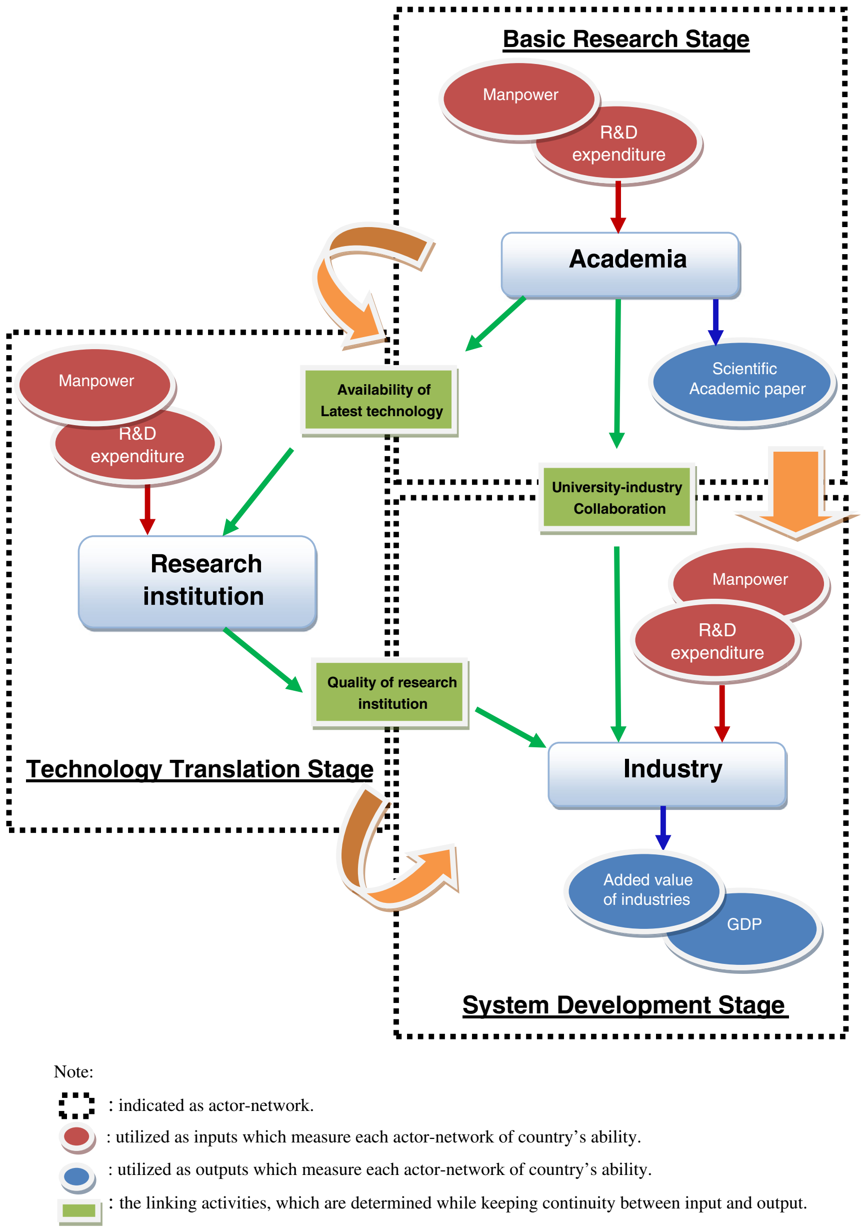

Fig. 1. The conceptual transformation framework of innovation system.

sector, such as technology transfer, patent licensing, co-development and a variety of others.

Hence, this study analyzed the data using a simple Network DEA model exhibited in Fig. 1, where the squares, red and blue circles indicate actors, inputs and outputs, respectively. The green lines express linking activities between sectors. By using the network DEA method, this study evaluated three-stage performance models, namely, research efficiency, translation efficiency and economic efficiency. In this way, this study can analyze and identify the benchmarking objectives at each stage, and clarified the important factors of overall R&D performance in the actor-network innovation system.

3.2. Data selection and description

The choice of input and output variables was devised based on previous literature on this topic (Balzat and Hanusch, 2004; Liu and White, 2001; Nasierowski and Arcelus, 2003). Each indicator used in the research model is shown in Fig. 1. As shown in Fig. 1, the research efficiency model (basic research stage from the academia angle), measuring the academic institution of each country's ability to generate publications, latest technology and collaborations with industries, consists of two inputs (R&D expenditure and personnel form high education sector), and three outputs (scientific academic papers, availability of latest technology, and university-industry collaboration). The translation efficiency model (technology translation stage from the research institution angle), measuring the research institution of each country's ability to transform the R&D into the industrial use, consists of three inputs (R&D expenditure and personnel form government and non-profit research institution sector, and the availability of latest technology), and one outputs (quality of research institution). Because there are linking activities between academia and research institution in the actor-network innovation system, the availability of latest technology variable in the technology translation stage indicates that parts of the outputs from academia sector are utilized as inputs to the research institution sector. The economic efficiency model (system development stage from the industry angles), measuring the business enterprise's ability, consists of four inputs (R&D expenditure and personnel form business enterprise sector, university-industry collaboration and quality of research institution), and two outputs (GDP and added value into industry). In the system development stage, there are comprised of relative linking activities, such as collaboration with academia institutions or licensing activities from research institutions. Hence, the university-industry collaboration variable in this study indicates that parts of the outputs from academia sector are utilized as inputs to the business enterprise sector, and the quality of research institution variable indicates that parts of the outputs from research institution sector are utilized as inputs to the business enterprise sector. The definitions of all indicators used in the research model are listed in Table 1.

A total of 25 countries form the sample used in the study. Twenty-two samples are OECD members and three are non-OECD economies. Table 2 shows the descriptive statistics. Data for analysis was derived from the OECD.Satat Extracts (OECD) between 2006 and 2008 (OECD, 2012), Web of Science (WOS) for the year of 2009, and The Global Competitiveness Report (GCR) published by World Economic Forum for the year 2009. Moreover, the output in research and development production is lagged, but with lag structure which is not fixed (Bonaccorsi and Daraio, 2003; Chen and Guan, 2012; Ravenscraft and Scherer, 1982). Hence, this study took 3 years delay between inputs and outputs in each sub process during the whole innovation possesses. Besides, all the economic data were also deflated by the gross domestic products index and added value of industries in each country by taking 2011 as the base year. This means that the differed performance in the whole innovation process, that is, the research and development production period of each country, amounts to 5 years. The above database and reports are commonly deemed as valid and reliable for the analysis. In addition, the number of analyzed countries is 25, which is greater than twice the selected twelve factors for the model in this study. According to Golany and Roll (1989), the number of DMUs should at least twice of the total number of input and output factors considered when using the DEA model. Hence, we concluded that the developed network DEA model for actor-network innovation performance model holds the construct validity.

3.3. Methodology

This paper set up a cross-country innovation system framework for R&D activities in 25 countries. Each country is regarded as a DMU that employs R&D expenditure and manpower as inputs to produce quantity and quality output indicators. Inspired by Tone and Tsutsui (2009), we proposed a network DEA model to analyze the relative efficiency of R&D activities.

Network DEA evaluates the efficiencies of multi-divisional organizations, and solves the comparative overall efficiency of country along with the divisional efficiencies in a unified framework. Previous studies had proposed the network DEA model to utilize the radial measure of efficiency in the traditional DEA model (Färe and Grosskopf, 2000; Lewis and Sexton, 2004; Löthgren and Tambouur, 1999; Prieto and Zofio, 2007). Tone and Tsutsui (2009) introduced the network slacks-based measure (SBM) approach for evaluating efficiency. The SBM approach is used for measuring efficiency when inputs and outputs may change non-proportionally. In this way, we can evaluate the total efficiency of each actor-network of the country among the set of DMUs as main objective which involves divisional efficiencies as its components. Because this study account for both input and output slacks, we used the non-oriented variable returns-to-scale model for evaluate the efficiency of DMUs.

The production possibility set $\{(x^k, y^k, z^{(k,h)})\}$ is defined as bellowed.

$$x^k \geq \sum_{j=1}^{n} x_j^k \gamma_j^k \ (k = 1, \ldots\ldots, K)$$

$$y^k \leq \sum_{j=1}^{n} y_j^k \gamma_j^k \ (k = 1, \ldots\ldots, K)$$

$$z^{(k,h)} = \sum_{j=1}^{n} z_j^{(k,h)} \gamma_j^h \ (\forall (k,h)) \ \text{(as inputs to h)} \quad (1)$$

$$z^{(k,h)} = \sum_{j=1}^{n} z_j^{(k,h)} \gamma_j^k \ (\forall (k,h)) \ \text{(as outputs from k)}$$

$$\sum_{j=1}^{n} \gamma_j^k = 1 (\forall k), \gamma_j^k \geq 0 (\forall j, k)$$

Where $x_j^k \in R_+^{m_k}$ and $y_j^k \in R_+^{r_k}$ are the inputs and outputs to DMUj at division *k*. $z_j^{(k,h)} \in R_+^{t_{(k,h)}}$ is linking inputs to DMUj at division *h* from division *k*, or also linking outputs to DMUj at division *k* from division *h*. $\gamma^k \in R_+^{n}$ is the intensity vector corresponding to division *k*.

Furthermore, this model corresponds to the situation where the intermediate activities are beyond the control of each innovation system. As regard to the linking constraints, we thus assumed that all data are positive and the linking activities are freely determined while keeping continuity between input and output:

$$z^{(k,h)} \gamma^h = Z^{(k,h)} \gamma^k \quad (2)$$

Where $z^{(k,h)} = (z_1^{(k,h)}, \ldots \ldots, z_n^{(k,h)} \in R_+^{t_{(k,h)} \times n}$

Table 1
Indicators in the conceptual model.

Stage (Actor)	Indicators	Item	Units	Data source
Basic research stage (Academia)	GERD_A	R&D expenditure on science and technology performed by high education sector	Million US dollars	OECD (2006)
	Personnel_A	Number of science and technology personnel from high education sector	Persons (full-time equivalent units)	OECD (2006)
	SA	Number of scientific academic paper	No.	WOS (2009)
	ALT	Availability of latest technology	Scale	GCR (2009)
	UIC	University industry collaboration	No.	GCR (2009)
Technology translation stage (Research institution)	GERD _R	R&D expenditure on science and technology performed by government and non-profit research institution sector	Million US dollars	OECD (2006)
	Personnel_R	Number of science and technology personnel from government and non-profit research institution sector	Persons (full-time equivalent units)	OECD(2006)
	QRI	Quality of research institution	Scale	GCR (2009)
System development stage (Industry)	GERD _I	Percentage of Gross R&D expenditure on science and technology performed by business enterprise sector	Million US dollars	OECD (2008)
	Personnel_I	Number of science and technology personnel from business enterprise sector	Persons (full-time equivalent units)	OECD (2008)
	GDP	Gross domestic products	Million US dollars	OECD (2011)
	AVI	Added value of industries	Million US dollars	OECD (2011)

OECD: OECD.Satat Extracts; WOS: Web of Science; GCR: The Global Competitiveness Report.

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Table 2
Descriptive statistics for the 25 countries.

	Mean	Minimum	Maximum	Std. dev.
GERD _A	3806.82	30.22	17,581.3	4218.86
Personnel_A	45,739.3	5612	214,006	51,036.9
SA	27,429.7	5587	82,353	23,518.3
ALT	5.89	4.4	6.6	0.58
UIC	4.70	3	5.6	0.77
GERD _R	294.58	13.77	3588.82	530.369
Personnel_R	20,112	78,357	800	585.622
QRI	5.25	3.4	6.2	0.65
GERD _I	14,266.3	585.62	116,258	24,437.3
Personnel_I	99,465.3	8100	625,264	136,452
GDP	67,917,714.4	155,992.28	1,172,803,400	249,374,489.2
VAI	649,542	90,367.9	2,864,332	672,415

Furthermore, we employ the following objective function and define the overall efficiencies corresponding to non-oriented orientation by:

$$\rho_0^* = \min \frac{\sum_{k=1}^{K} w^k \left[1 - \frac{1}{m_k}\left(\sum_{i=1}^{m_k} \frac{s_{io}^{k-}}{x_{i0}^k}\right)\right]}{\sum_{k=1}^{K} w^k \left[1 + \frac{1}{r_k}\left(\sum_{r=1}^{r_k} \frac{s_{ro}^{k+}}{y_{r0}^k}\right)\right]} \quad (3)$$

In this study, we define the divisional efficiency score of division k by

$$\rho_k = \frac{1 - \frac{1}{m_k}\left(\sum_{i=1}^{m_k} \frac{s_{io}^{k-}}{x_{i0}^k}\right)}{1 + \frac{1}{r_k}\left(\sum_{r=1}^{r_k} \frac{s_{ro}^{k+}}{y_{r0}^k}\right)} \quad (4)$$

4. Results and analysis

4.1. Overall R&D performance analysis

The evaluation of a country's research efficiency, translation efficiency and economic efficiency is conducted by the network DEA approach in this study. Previous studies consider the overall efficiency measure of the innovation system as black box (Guan and Chen, 2012; Li, 2009; Zabala-Iturriagagoitia et al., 2007) and neglect the operation of the interacting sub-processes within it (Yang and Liu, 2012; Guan and Chen, 2012; Kao, 2009; Färe and Grosskopf, 2000). This study employed the network DEA model for overall efficiency and the three component efficiencies with the consideration of the interdependent relationship between three sub-processes. It is desirable that the employed network DEA model makes the component efficiency measures connected in the virtue of constructing a network production frontier. We also presented the cooperative and interdependent efficiency measures for the three sub-processes in this study.

The overall efficiency is classified into research efficiency, translation efficiency and economic efficiency, which is shown in the Table 3. The average score of the overall efficiency computed from the network DEA model is 0.404. The top six countries with high scores perform efficiently in all stages, including New Zealand, Poland, Italy, Switzerland, Ireland, and Germany. Furthermore, the average scores of the research efficiency, translation efficiency and economic efficiency, which are based on the network relationship, are 0.895, 0.657, and 0.740, respectively. As for the decomposition of overall R&D performance, the basic research stage has a higher average score and more efficient courtiers than two other stages. This can be explained that most of countries employ more national R&D resources on the basic research. It implied that the resource allocation on the basic research stage for these countries is regards as the most important technology policy. However, the results of this study indicated that although these countries have higher research efficiencies, they could not also have higher overall efficiencies than other countries. The high overall performance of the countries, such as Japan, Korea, and United Kingdom, may be attributed to their better performances in the system development stage. In addition, the results of this study also indicated the average score of the translation efficiency is lowest than two other efficiencies. It is obvious that most countries ignore the importance of technology translation. Because the research results of the academia are too novel to be commercialized, academic R&D may or may not be applied to practical use and industrial need. Hence, academic R&D needs some help to make use of every possible method of technology translation in order to transform new technology into the industrial application. It is suggested that science & technology policy maker should put more resources on the technology translation stage. For example, government could fund the private sector directly to improve processes, systems or services that could increase the companies' sales and profits. In addition, manager should also endeavor to improve academia R&D and the ability of technology translation in the whole innovation system, so as to increase the opportunities of technology transfer and diffusion for industries.

4.2. Constructing the efficiency group for benchmark-learning

This study examined each country by network DEA analysis. Table 4 maps out all the countries according to their performance in the different sub-processes. This performance group categorized all DMUs into four types: benchmark group, the basic research innovation driven group, technology translation innovation driven group and system development innovation driven group. Six countries, including New Zealand, Poland, Italy, Switzerland, Ireland, and Germany, can be regarded as the productivity benchmark of other countries and their efficiencies at each stage reach at above 0.999. It means that benchmark group uses the network resources to perform the innovation system efficiently at each stage. Twelve countries are categorized as the basic research innovation driven group, and their research efficiencies are higher than translation efficiencies and economic efficiencies. These countries are more efficient at the basic research stage. Seven countries belong to the technology translation innovation driven group but they are less efficient at basic research and system development stage

Table 3
Efficiency scores of the 25 countries.

No.	Nation	Overall efficiency	Efficiency at each stage		
			Research efficiency	Translation efficiency	Economic efficiency
1	Australia	0.022	0.881	0.342	0.555
2	Austria	0.016	0.892	1.000	0.567
3	Belgium	0.018	1.000	0.542	0.667
4	Canada	0.041	1.000	0.216	0.668
5	Czech Republic	0.330	1.000	1.000	0.645
6	Denmark	0.091	1.000	1.000	0.417
7	Finland	0.005	0.729	0.532	0.359
8	France	0.015	0.671	0.089	0.647
9	Germany	0.936	1.000	1.000	0.999
10	Ireland	0.956	1.000	1.000	0.999
11	Italy	0.996	1.000	0.999	1.000
12	Japan	0.511	0.513	0.020	1.000
13	Korea	0.701	1.000	0.103	1.000
14	Netherlands	0.015	0.985	0.393	0.626
15	New Zealand	1.000	1.000	1.000	1.000
16	Norway	0.274	0.999	1.000	0.748
17	Poland	1.000	1.000	1.000	1.000
18	Portugal	0.020	0.766	0.370	0.716
19	Spain	0.397	0.871	0.667	0.904
20	Sweden	0.125	1.000	1.000	0.511
21	Switzerland	0.970	0.999	1.000	0.999
22	United Kingdom	0.600	0.731	0.079	1.000
23	Singapore	0.040	0.586	0.947	0.736
24	South Africa	0.911	0.762	1.000	0.245
25	Taiwan	0.108	1.000	0.119	0.479
Average		0.404	0.895	0.657	0.740

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while being efficient at the technology translation stage. Four countries have greater economic efficiencies than the two other efficiencies. The results indicated that they perform well at the system development stage.

The Kruskal-Wallis test was used to analyze differences at each sub-process across four groups in our model. All of the differences across four groups and performance outcomes were significant at the acceptable level (See Table 5). The results indicated the difference of efficiency group categorized in this study is discernment. Therefore, the efficiency group map could provide guide on how to improve the overall performance of a country's innovation system from process perspective. The network DEA approach in this study provides a good opportunity to screen out specialized efficient country at each sub-process for benchmark-learning. For example, all countries categorized as the system development innovation driven group are inefficient at the technology translation stage, while their research efficiencies and economic efficiencies are quite higher. It is suggested that science & technology policy maker should funded the various agents, such as non-profit research institute, to promote the new technology diffusion, and also enhance the university-industry collaboration to bridge the gap between academia and business enterprise.

4.3. Sensitivity analysis

Since each country has its own inherent tradeoffs among the multiple measures, it is important for the policy maker to identify the critical factors that significant influence the overall efficiency. This study used the sensitivity analysis to determine the influence effect of overall efficiency by the removal of each input measure. The results of the sensitivity analysis in this study could identify the significant order of the input factor at each stage, and provide the reference framework for R&D investment decision-making.

Table 6 lists the calculated results. Considering the importance ranking within the same stage, Manpower is the important factor in the basic research and technology translation stage. However, the R&D manpower from business enterprises is not the primary influencing factor in the system development stage. This could be explained that the number of personnel engaged in R&D is directly linked to the R&D efforts. The greater quantity and quality of the human capital developed from education system could foster overall growth in the knowledge-based economy. In addition, although companies need the well-trained personnel for technology commercialization, they tend to cooperate with university and research institute for cultivating R&D talent. Hence, this study suggested that government could support their funding, and further promote cooperative R&D among industry, academia and research institutes to quickly cultivate talents and establish core technologies.

Furthermore, quality of research institution is ranked the highest influencing factor in the system development. This is also the most important factor of the cross-stage relative importance comparisons. This could be explained that the research institution plays the critical role for apply the scientific knowledge into industries practice between academia and industry. There is the gap in access to the market at the critical step in the development of new technology. The missing middle often occurs at the stage of translation development where opportunity and uncertainty are high. Hence, this study suggested that the government should strengthen the mechanism for technology commercialization. One of the most effective ways to upgrade basic research R&D and speed up the success of the commercialization is to development and transfer industrial technology from research institutions to industry. Through the mediator role of the research institution, government's active technology innovation strategies can help enterprises from the stage of R&D, product development, to new business application effectively.

Table 4
Efficiency scores of each group.

Group	Nation	Overall efficiency	Efficiency at each stage		
			Research efficiency	Translation efficiency	Economic efficiency
Benchmark	New Zealand	1.000	1.000	1.000	1.000
	Poland	1.000	1.000	1.000	1.000
	Germany	0.936	1.000	1.000	0.999
	Ireland	0.956	1.000	1.000	0.999
	Italy	0.996	1.000	0.999	1.000
	Switzerland	0.970	0.999	1.000	0.999
	Average	0.976	0.999	0.999	0.999
Basics research innovation driven	Australia	0.022	0.881	0.342	0.555
	Belgium	0.018	1.000	0.542	0.667
	Canada	0.041	1.000	0.216	0.668
	Czech Republic	0.330	1.000	1.000	0.645
	Denmark	0.091	1.000	1.000	0.417
	Finland	0.005	0.729	0.532	0.359
	France	0.015	0.671	0.089	0.647
	Korea	0.701	1.000	0.103	1.000
	Netherlands	0.015	0.985	0.393	0.626
	Portugal	0.020	0.766	0.370	0.716
	Sweden	0.125	1.000	1.000	0.511
	Taiwan	0.108	1.000	0.119	0.479
	Average	0.124	0.919	0.476	0.608
Technology translation innovation driven	Austria	0.016	0.892	1.000	0.567
	Czech Republic	0.33	1.000	1.000	0.645
	Denmark	0.091	1.000	1.000	0.417
	Norway	0.274	0.999	1.000	0.748
	Sweden	0.125	1.000	1.000	0.511
	Singapore	0.040	0.586	0.947	0.736
	South Africa	0.911	0.762	1.000	0.245
	Average	0.255	0.891	0.992	0.552
System development innovation driven	Japan	0.511	0.513	0.020	1.000
	Korea	0.701	1.000	0.103	1.000
	Spain	0.397	0.871	0.667	0.904
	United Kingdom	0.600	0.731	0.079	1.000
	Average	0.522	0.779	0.217	0.976

Table 5
Kruskal-Wallis test of efficiency scores at each group.

Efficiency at each stage	Group	No.	Efficiency average	Kruskal-Wallis test (P-value)
Overall efficiency	Benchmark	6	0.976	14.987***
	Basics research innovation driven	12	0.124	
	Technology development innovation driven	7	0.255	
	System development innovation driven	4	0.522	
Research efficiency	Benchmark	6	0.999	5.238*
	Basics research innovation driven	12	0.919	
	Technology development innovation driven	7	0.891	
	System development innovation driven	4	0.779	
Translation efficiency	Benchmark	6	0.999	13.940***
	Basics research innovation driven	12	0.476	
	Technology development innovation driven	7	0.992	
	System development innovation driven	4	0.217	
Economic efficiency	Benchmark	6	0.999	16.696***
	Basics research innovation driven	12	0.608	
	Technology development innovation driven	7	0.552	
	System development innovation driven	4	0.976	

* < 0.1, ** < 0.05, *** < 0.01.

5. Conclusions

In this study, we have developed a network DEA model to deal with the structural and functional complexity of the innovation processes at a national level. The approach provided an experimental tool to examine the efficiency of R&D activities both individually and in combination. Assessing the R&D efficiency also helped both to identify the best the innovation practitioners for benchmarking and to shed light on ways to improve efficiency by highlighting areas of weakness. Along with the network SBM analysis for measuring the divisional efficiencies in a unified framework, the model supports policy makers to reveal structures for performance evaluating and also develop and test strategies for the R&D investment decision-making. The empirical results of this study showed that most of countries employ more national R&D resources on the basic research and the research efficacy presents a higher average score at the basic research stage. As for the decomposition of overall R&D performance, policy makers are suggested to formulate a strategy characterized by symmetry in its objectives, aiming at improving academia R&D and the ability of technology translation in the whole innovation system so as to increase the opportunities of technology transfer and diffusion for industries. According the DEA results of this study, this study also screened out specialized efficient country at each sub-process and further constructed the efficiency group for benchmark-learning. The critical measure reveals that New Zealand, Poland, Italy, Switzerland, Ireland, and Germany are the most efficient countries.

The presented model also integrated the actor-network theory into a dynamic consideration of the innovation system. We offered an alternative perspective and characterization of the divisional efficiencies of the innovation system via three-stage process that emphasizes the effect of linking activities. By using the actor-network approach, we could “follow the actor” (Latour, 1987) and identify the inefficiency of the multi-divisional innovation system. The empirical results of this study indicated that there is the gap in access to the market at the critical step in the development of new technology. This result is in accordance with the previous studies by Holdren (2012) that there are technology transition challenges between invention and commercialization to bridge the valley of death. They suggested that national R&D investments must align more fully with similar investments by the private sector. Hence, partnerships among diverse actors are a keystone of innovation strategy to bridge a gap. For example, the government could create national public-private partnerships to upgrade basic research R&D for speeding up the technology commercialization through the linking role of the research institution. The empirical result indicated that the research institution can help enterprises from the stage of R&D, product development, to new business application effectively. This study thus suggested that policy maker could support academia - research institution - industry partnerships for accelerating the investment in and development of R&D activities.

In addition, the empirical result showed that the number of personnel engaged in R&D is directly related to the R&D efforts. However, R&D manpower is not the important factor in the system development stage. This can be explained by the fact that the quantity and quality of the human capital developed from education system do not meet the talented need of industry. Disparity between knowledge acquired by students in their higher education studies and skills needed by the industry and employers, along with the problem of an unmet talent demand, has become emergent as the economic problem deepens.

Table 6
Sensitivity analysis.

		Overall		*Basic research stage*		*Technology translation stage*		*System development stage*	
		Overall Efficiency	Ranking	Research Efficiency	Ranking	Translation Efficiency	Ranking	Economic Efficiency	Ranking
Efficiency score		0.404		0.895		0.657		0.740	
Removal of input	*GERD _A*	0.382	7	0.826	2	0.643		0.695	
	Personnel_A	0.392	9	0.774	1	0.673		0.742	
	ALT	0.364	5	0.864	3	0.634	3	0.756	
	GERD _R	0.351	3	0.872		0.593	2	0.728	
	Personnel_R	0.330	2	0.887		0.462	1	0.710	
	UIC	0.360	4	0.878		0.633		0.719	2
	QRI	0.239	1	0.865		0.503		0.670	1
	GERD _I	0.375	6	0.882		0.632		0.730	3
	Personnel_I	0.387	8	0.893		0.651		0.771	4

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This study thus suggested that policy maker could promote education-job match in the cultivation of talent education system for industries. For example, the higher education system can develop cooperative education and customized education implemented with industry. A greater quantity and quality of the human capital developed from education system should be able to foster overall growth in the knowledge-based economy.

Through empirical analysis on the actor-network perspective, this study enhances the understanding of divisional efficiencies of the innovation system that emphasizes the effect of linking activities. This study also provided managerial implications for the government's industrial policy, especially on national R&D resource allocation strategies for constructing the ecosystem. The decision-maker needs to be well coordinated in the linking activities among different actors in the innovation system. These investments on linking activities will have the expected benefits on technological innovation for accelerating the research and development in the ecosystem. In addition, it also can bridge gaps in the present innovation system, particularly the gap between the research activities and development for industrial use.

This study has some limitations for the comparison of R&D performance across country. First, the presented model reveals that there are collaborations and linkages between actors, so that we used the quality factors as efficiency measures. In this situation, the measurement could be improved by collecting more detailed measures in the future work. Second, the weight used for divisional efficiency evaluation in the whole innovation system, even though our results seem robust to alternating each division efficiency weights, required further studied. Third, the number of time lags from initiation of the R&D projects by academia to the realization of the output varies from case to case, and the deferred effect of R&D investment is still open to discussion across country.

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Ping-Chuan Chen is currently the Adjunct Assistant Professor at the Executive Master Program of Business Administration in Biotechnology, College of Management, Taipei Medical University of Taiwan. He received his Ph.D. from the Department of Business Administration of National Central University, Taiwan. Before this, Dr. Chen earned his M.S. from Yuan-Ze University of Taiwan and completed his L.L.B. from National Chung-Hsing University of Taiwan. His researches mainly focus on areas of technology management, entrepreneurship and innovation management. Dr. Chen has had articles published in the *International Journal of Operations & Production Management, Transportation Planning and Technology, Technology Analysis & Strategic Management, Technology in Society* and other journals.

Shiu-Wan Hung is currently the Distinguished Professor and Director at the Department of Business Administration of National Central University, Taiwan. She received her Ph.D. from the Institute of Business and Management of National Chiao Tung University, Taiwan. Before this, Dr. Hung earned her M.S. from the University of Wisconsin-Madison in USA and completed her B.S. from National Chengchi University of Taiwan. Her researches mainly focus on areas of technology management, knowledge management and performance management. Dr. Hung has had articles published in the *Information & Management, Scientometrics, Technovation, Computers & Operations Research, European Journal of Operational Research, Omega-International Journal of Management Science* and other journals.

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