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R&D EFFICIENCY IN THE USA: AN APPLICATION OF DEA

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ABSTRACT

R&D has been recognized as one of the main drivers of economic growth. Understanding the importance R&D in economic growth, research has focused on R&D efficiency of nations. Extant research has not looked at the R&D efficiency of regions. This paper analyses R&D efficiency across 50 US states and the District of Columbia using Data Envelopment Analysis (DEA). DEA is a non-parametric estimation technique which assesses the performance of decision making units (DMUs) based on actual performance. Taking R&D expenditures and R&D personnel as inputs and patents and publications as outputs of the research process, an attempt is made to assess the R&D efficiency of US states. Only seven states are found to be CRS, VRS and Scale Efficient. This research highlights the variations in relative R&D efficiency across US states.

Keywords: *Patents, R&D, Technical Efficiency, Scale Efficiency, VRS DEA. JEL Classification: O31, O32, C14, O50*

Introduction

Economic growth has been researched over several decades now. While various explanations have been put forward to explain the nature and causes of economic growth, it is generally accepted that research and development (R&D) plays a major role in economic growth. R&D is the core activity which generates new knowledge. This new knowledge has the potential to improve existing processes and products, or suggest newer processes which are more efficient. As efficiency levels increase due to sustained R&D, there is a rapid improvement in productivity. This improved productivity results in economic growth.

Developed countries are consistently investing in R&D to maintain their technological lead and gain competitive advantage. With rapid globalization, there is an increasing interest in replicating the success of the developed countries. Developing nations are following the example set by Germany, Japan and South Korea and are increasing their investments in R&D. As scarce resources are channelized into R&D, the focus is on the efficiency of the R&D process itself. Several studies of R&D efficiency have used patents and scientific publications as indicators of output, while R & D expenditure and the number of scientific personnel have been

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used as input indicators. There are some comparative studies of R&D efficiency at the national level, but few studies have looked at the R&D efficiency of regions within a particular country. While cross country studies have their relevance, there is a need to examine R&D efficiency within a nation to identify whether R&D efficiency is homogeneous across the regions of the country under study, or is it concentrated in a few regions. This analysis can help in the identification of the exceptional performers and laggards, and help focusing research to understand the reasons for the same. Thus, we would be able to develop policies which can replicate the success of a particular region in other parts of the country as well.

The continued leadership of the USA in the patents and scientific publications over a long period of time, the geographic structure of USA with a large number of states and the availability of data on R&D outputs and inputs for these regions has motivated us to study R&D efficiency in the states of USA. The rest of this paper is organized as follows. The second section presents a review of the existing literature on R&D and economic growth. The third section describes the methodology followed in the current work. The fourth section describes the data and the findings are presented in the fifth section. Section six summarizes the study and provides a conclusion.

Review of Literature

Friedrich List (1841) highlighted the role of R&D in economic growth and his concept of "techno-nationalism" further developed this thought. Schumpeter (1934) elaborated on these contributions and mentioned the critical role played by entrepreneurs in the process of economic growth. As the importance of R&D was recognized, organized R&D was embraced by governments and large industrial entities. This change from R&D by an inventor to R&D by a nation, region or an industrial entity was radical because the focus now was on allocation of resources to the R&D process and measurement of its output. Thus the concept of R&D by larger entities and the need for assessment of R&D efficiency arose. As governments increased public funding of R&D, a stream of research examined the impact of public R&D funding on private funding and productivity across and within regions (Link, 1982; Brockhoff, 1983; Leyden et al, 1989; Beise and Stahl, 1999; David et al, 2000; Hall and Reenen, 2000; Salter and Martin, 2001; Cohen et al, 2002; Guellec and De La Potterie, 2003; Garcia-Quevedo, 2004; Gorg and Strobl, 2007). While the research in this area has followed several approaches like econometric studies, case studies and surveys, the evidence on the impact of public funded R&D on private R&D has not been conclusive.

There are some studies that compare the R&D efficiency of various nations (Grupp, 1993; Teitel, 1994; Rousseau, 1997; Rousseau, 1998; Melciani, 2000; Sharma and Thomas, 2008) and some studies focus on subject areas, institutions, firms, policy programs or regions (Guan & Ma, 2004; Guan & Wang, 2004; Guan & He, 2005; Huang et al, 2006; Karkazis & Thanassoulis, 1998; Meng et al, 2006; Moed, 2002). One of the earlier works on R&D potential within a country is Muller and Nejedly (1971) which studies the regional structure of R&D in erstwhile Czechoslovakia. Their statistical analysis indicates that R&D potential is concentrated in a few localities which are usually centers of state administration, education and cultural life. A regional analysis of R&D efficiency has not been attempted in the USA to the best of our knowledge. As the United States of America has been one of the most prolific nations as far as patents and scientific publications are concerned, this paper focuses on measuring the R&D efficiency of states in the USA.

Methodology

Data envelopment analysis emerged out of the continued research interest in the problem of measuring the productive efficiency of an industry. Efficiency was loosely defined as the ability of a decision making unit (DMU) to produce as large as possible an output from a given set of inputs. Farell (1957) defined the term 'technical efficiency' as the DMU's success in producing maximum output. We illustrate the methodology by taking the case of a single output single input technology. We can calculate the average productivity as the ratio of the output to the input. Suppose a firm uses A x units of input x to produce A y units of output y . The average productivity (AP) for firm A would be defined as

$$AP_A = \frac{y_A}{x_A}$$

To calculate efficiency, we suppose that the technology is described by a production function.

$$y = f(x)$$

Then, is the maximum output producible from input A x .

The technical efficiency (TE) is calculated as the ratio of the actual productivity to the maximum attainable productivity by each DMU. For Firm A, the output oriented technical efficiency is

$$TE_O^A = \frac{y_A}{y_A^*} \leq 1$$

But as the inputs and outputs increase, it becomes very difficult to calculate with certainty the average productivity attributable to any one of the inputs. In order to solve this problem Charnes, Cooper and Rhodes (1978) formulated it as a linear programming (LP) problem which could be solved using the simplex method. This model measured the technical efficiency of the firm relative to a reference technology which exhibited constant returns to scale at each point on the production frontier and came to be known as the Constant Returns to Scale (CRS) Model. Each LP problem called the primal, has another closely related linear program called its dual. We can arrive at the optimal solution of the linear program by solving either the primal or its corresponding dual. At times, it is more convenient to solve the dual keeping in mind the computational and interpretative complexities.

Understanding the restrictive nature of this model, Banker, Charnes and Cooper (1984), developed the variable returns to scale model (VRS) which generalized the original CRS DEA model for technologies exhibiting increasing, constant or diminishing returns to scale at different points on the production frontier. The Scale efficiency is defined as the ratio of Constant Returns to Scale Technical Efficiency to the Variable Returns to Scale Technical Efficiency. VRSTE

$$S.E. = \frac{CRSTE}{VRSTE}$$

Increasing returns to scale hold when a small increase in the input x results in an increase in the average productivity. Decreasing returns to scale means an increase in input x leads to a decline in average productivity. Constant returns to scale means that an increase in input x leaves the average productivity unchanged.

This study uses the CRS as well as the VRS model to get better insights on the R&D efficiencies of various states. The constant returns to scale model has a constant slope, indicating that the average productivity measure as the ratio of output to input (in the single input single output case) is constant. It normally generates technical efficiency scores which are smaller than the VRS technical efficiency scores. The decision on the choice of input or output orientation of the model depends on the importance of input conservation or output augmentation. As the aim of this study is to highlight the efficiencies and inefficiencies in generating publications and patents, we chose the output oriented variable returns to scale model. The output oriented VRS model is presented in Appendix A.

Data

Patents have generally been accepted as indicators of the innovation and R&D process in the absence of more robust indicators (Griliches, 1990). The benefits of using patents as indicators has been the widespread availability of patent statistics collected over long periods of time across nations and regions. The USA has been able to provide patent statistics with breakup for its various states. At this point, we also need to mention the failings of patent data such as the argument "not all inventions are patented and not all patents are useful". Even in the face of such criticism, patents have become the most common indicator of innovative output. Another, albeit an academic indicator of the R&D process, is the number of scientific publications. While publications are a valuable source of information on innovative output, they may suffer from language bias (Rousseau, 1997). Publications include articles, letters, notes and reviews (Schubert et al, 1989). As most publications have multiple authors, some times from different countries, it becomes difficult to determine the contribution of different authors. Additionally it is also difficult to divide multiple author papers among various countries. Several methods have been developed to resolve both these issues (Schubert et al, 1989; Egghe et al, 2000). Even with these constraints, publication output is understood to be a valuable output indicator of the R&D process. The data on patents is collected from the US Patent and Trademark Office (USPTO) and the data on publications is compiled from the ISI Web of Knowledge Science Citation Index Expanded (v.4.1).

Most nations collect data on R&D expenditure. Following convention, nations attempt to provide details of expenditure on basic, applied and developmental research. In large countries like USA which have adopted a federal system of governance, the situation gets further complicated by federal funding of research in academic institutions, in business entities and non-profit organizations. Instead of concentrating on identifying the impact of public R&D on private R&D as has generally been the case, this paper attempts to look at the overall picture of R&D expenditure across the states of USA. The data on US R&D expenditure is collected from the National Science Foundation, Division of Science Resources Statistics.

Another input to the R&D process is the availability of scientific personnel. While the details of scientific personnel are the generally not available for most countries for any reasonable length of time, the USA is able to give a state-wise breakup of personnel in science and engineering (S&E) occupations. This helps in understanding the impact of personnel on standard indicators of R&D outputs such as patents and publications. This data on personnel in S&E occupations is taken from the National Science Board, Science and Engineering Indicators 2008 publication.

Another issue in the assessment of R&D efficiency is the presence of a time lag between the provision of inputs and the expectation of outputs. Following Goto and Suzuki (1989), we take a three year time lag between the input and the output data. The data on patents and publications are taken for the year 2006, while the data on aggregate R&D expenditure is taken for the 2003. The data on the number of scientific personnel is not available for the year 2003; hence we use the data for the year 2004. This is done as the number the number of scientific personnel is not expected to exhibit sudden variations from the previous year. Data is available for the District of Columbia for all the inputs and outputs, and we observe that it has outputs comparable and exceeding most states. Hence the District of Columbia is also included in our analysis along with the 50 states in the USA taking the total number of decision making units to 51. The input and output data used for this study are given in Appendix B.

Findings

This paper aims to identify whether there are any regional variations in the R&D efficiency across states in the USA. 50 states and the District of Columbia are included in this analysis. The results on technical efficiency and returns to scale are presented below (Table 1).

Table 1: Technical and Scale Efficiency in 51 US regions

States	CRSTE	VRSTE	SE	RTS
Leaders				
California	0.74	1.00	0.74	drs
Florida	0.72	1.00	0.72	drs
Hawaii	1.00	1.00	1.00	crs
Idaho	1.00	1.00	1.00	crs
Iowa	1.00	1.00	1.00	crs
Louisiana	0.91	1.00	0.91	drs
Maryland	1.00	1.00	1.00	crs
Massachusetts	1.00	1.00	1.00	crs
Montana	1.00	1.00	1.00	crs
New Mexico	0.94	1.00	0.94	irs
New York	0.93	1.00	0.93	drs
Vermont	0.99	1.00	0.99	irs
Wyoming	1.00	1.00	1.00	crs
Followers				
North Dakota	0.71	0.97	0.73	irs
Oregon	0.82	0.95	0.86	drs
Georgia	0.67	0.95	0.71	drs
Texas	0.57	0.94	0.60	drs
Minnesota	0.71	0.92	0.77	drs
Rhode Island	0.78	0.91	0.86	irs
Pennsylvania	0.82	0.89	0.93	drs
Missouri	0.69	0.88	0.78	drs
Delaware	0.77	0.88	0.88	irs
Wisconsin	0.71	0.87	0.82	drs
Tennessee	0.83	0.86	0.96	drs
Utah	0.80	0.85	0.94	drs
North Carolina	0.78	0.84	0.93	drs
Kentucky	0.72	0.84	0.86	drs
Nevada	0.79	0.81	0.97	drs
Oklahoma	0.73	0.81	0.89	drs
Arkansas	0.76	0.81	0.94	drs
South Carolina	0.72	0.80	0.90	drs
Nebraska	0.72	0.80	0.91	drs
Arizona	0.65	0.79	0.82	drs
District of Columbia	0.75	0.79	0.96	drs
Hopefuls				
Washington	0.68	0.76	0.89	drs
South Dakota	0.75	0.76	0.99	irs
Indiana	0.74	0.75	0.98	drs
Colorado	0.62	0.75	0.82	drs
Ohio	0.68	0.73	0.93	drs
Illinois	0.65	0.72	0.90	drs
Mississippi	0.64	0.72	0.88	irs
New Hampshire	0.69	0.71	0.97	irs
Alaska	0.62	0.70	0.88	irs
Maine	0.68	0.69	0.97	drs
Connecticut	0.67	0.67	0.99	drs
Michigan	0.57	0.67	0.85	drs
West Virginia	0.62	0.64	0.97	irs
New Jersey	0.53	0.64	0.83	drs
Alabama	0.58	0.60	0.96	drs
Laggards				
Virginia	0.33	0.47	0.70	drs
Kansas	0.43	0.46	0.92	drs

CRSTE - Constant Returns to Scale Technical Efficiency
VRSTE – Variable Returns to Scale Technical Efficiency
SE – Scale Efficiency
IRS – Increasing Returns to Scale
CRS – Constant Returns to Scale
DRS – Decreasing Returns to Scale
RTS – Returns to Scale

The results have been sorted according to the VRSTE scores which enable us to divide the 51 regions into 4 groups. Group 1 consisting of 13 states has been named the "Leaders" because all of them achieve VRSTE scores of 1. This indicates that all these states lie on the VRS technical efficiency frontier. Group 1 has 7 states which exhibit constant returns to scale, 4 which exhibit decreasing returns to scale and 2 which exhibit increasing returns to scale. As discussed earlier, the increasing and decreasing returns to scale indicate increase or decline in average productivity respectively. Thus California which exhibits a scale efficiency of 0.74 should be able to achieve the same level of output with lesser inputs indicating downward movement on the efficiency frontier.

Group 2 has a total of 21 member states, out of which only 3 exhibit increasing returns to scale. The rest 18 exhibit decreasing returns to scale. As the VRSTE scores of this group ranges from 0.97 to .79, we label this group as the "Followers". Looking at Group 3, we can see that it has 15 states with VRSTE scores ranging from 0.76 to 0.60. This group has 10 states which exhibit decreasing returns to scale and 5 states which show increasing returns to scale. We label this group as the "Hopefuls". Finally we are left with two states Virginia and Kansas which exhibit decreasing returns to scale and low values of VRSTE. This indicates that out of all the 51 regions, these two states have the lowest technical efficiency.

While the VRSTE scores indicate the relative pure technical efficiency or inefficiency, further analysis of the performance requires a comparison of the actual values of the inputs and outputs. As the comparison would become cumbersome for 51 regions, we concentrate on comparing the ranks for the Leaders and the Laggards based on input and output data for the latest available years (Table 2).

Table 2: Efficiency Scores and Ranks for Leaders and Laggards

States	CRSTE	VRSTE	SE	RTS	PAT RANK	PUB RANK	EXP RANK	PER RANK
				Leaders				
California	0.74	1.00	0.74	drs	1	1	1	1
Florida	0.72	1.00	0.72	drs	11	12	17	4
Hawaii	1.00	1.00	1.00	crs	46	38	46	43
Idaho	1.00	1.00	1.00	crs	20	44	35	39
Iowa	1.00	1.00	1.00	crs	27	27	31	33
Louisiana	0.91	1.00	0.91	drs	37	30	37	32
Maryland	1.00	1.00	1.00	crs	21	4	4	13
Massachusetts	1.00	1.00	1.00	crs	4	3	3	8
Montana	1.00	1.00	1.00	crs	44	42	48	47
New Mexico	0.94	1.00	0.94	irs	38	26	19	34
New York	0.93	1.00	0.93	drs	3	2	6	3
Vermont	1.00	1.00	1.00	irs	32	46	43	46
Wyoming	1.00	1.00	1.00	crs	50	50	51	51
				Laggards				
Virginia	0.33	0.47	0.70	drs	23	16	13	5
Kansas	0.43	0.46	0.92	drs	31	34	28	27

PAT RANK indicates Patent Rank and is calculated for all 51 regions for the year 2006.

PUB RANK indicates Publication Rank and is calculated for all 51 regions for the year 2007.

EXP RANK indicates R&D Expenditure Rank and is calculated for all 51 regions for the year 2004.

PER Rank indicates Personnel Rank and is calculated for all 51 regions for the year 2004.

CRSTE - Constant Returns to Scale Technical Efficiency

VRSTE – Variable Returns to Scale Technical Efficiency

SE – Scale Efficiency

IRS – Increasing Returns to Scale

CRS – Constant Returns to Scale

DRS – Decreasing Returns to Scale

RTS – Returns to Scale

While California, Massachusetts and New York seem to show high levels of performance, a closer inspection reveals that only Massachusetts exhibits constant returns to scale out of these three. New York and California are able to achieve VRS technical efficiency because of extensive use of inputs highlighted by their high ranks on the R&D expenditure and personnel and the fact that both of them have decreasing returns to scale. Among the laggards, Virginia has a high rank in scientific personnel but this advantage is not translating into either patents granted or publications. This indicates that Virginia is not able to utilize its R&D inputs efficiently. Kansas has the lowest VRS technical efficiency of 0.46 which indicates that there is a scope for improvement in the use of R&D resources.

Conclusions

In this study an attempt is made to assess the relative R&D efficiency of 51 US regions. The USA is chosen because of its prolific publishing and patenting activity over the years. The inputs taken are R&D expenditure and the number of personnel in scientific occupations. Only 7 states are found to be CRS, VRS and Scale efficient. The analysis indicates that there is a wide variation in the performance of different US states. Some of the states like New York and California which have large amounts of resources are able to produce significant output but there is a scope for improvement because they have decreasing returns to scale. On the other hand, states like Virginia and Kansas have very low relative VRS technical efficiency scores of 0.47 and 0.46 indicating scope for improvement. This study contributes by identifying leader and laggard states and thus presents benchmarks which can be followed and assessed for policy interventions.

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Appendix A

The formulation of the output oriented Variable Returns to Scale (VRS) Model is as below.

$$\max_{\theta,\lambda} \theta_m$$

such that

$$Y\lambda \geq \theta Y_m$$
$$X\lambda \leq X_m$$
$$\sum_{n=1}^{N} \lambda_n = 1$$

$$\lambda \geq 0; \ \theta_m \text{ unrestricted.}$$

Where θ is a scalar corresponding to the equality constraint that normalizes the weighted sum of outputs of the primal problem.

λ is the dual variable corresponding to the other inequality constraints of the primal. It acts as a weight for the firms.

n stands for the number of DMUs, n = 1, 2, …., N.

m stands for the mth Decision Making Unit (DMU).

X stands for the matrix of inputs.

Y stands for the matrix of outputs.

The constraint $\sum_{n=1}^{N} \lambda_n = 1$ is termed a convexity constraint, and was introduced by Banker et al (1984).

Appendix B

S.No.	States	PAT	PUB	EXP	PER
1	Alabama	430	4278	2543	57560
2	Alaska	45	777	321	10660
3	Arizona	1893	6109	3578	95380
4	Arkansas	185	1739	509	22150
5	California	25043	50203	59664	693670
6	Colorado	2349	8071	5012	126280
7	Connecticut	1857	6851	6548	82820
8	Delaware	396	1821	1414	17980
9	District of Columbia	69	5777	2686	57750
10	Florida	3263	11877	5172	229950
11	Georgia	1719	9677	3923	141710
12	Hawaii	101	1893	438	16360
13	Idaho	1717	1126	1209	22310
14	Illinois	4053	16275	11045	219530
15	Indiana	1499	7122	4487	79120
16	Iowa	732	4656	1451	39280
17	Kansas	581	2430	2024	52020
18	Kentucky	471	3048	1014	44350
19	Louisiana	365	3978	954	42230
20	Maine	156	1024	372	15160
21	Maryland	1558	23086	10162	154310
22	Massachusetts	4369	26356	15638	186260
23	Michigan	4179	11912	16884	183140
24	Minnesota	3268	8421	5842	119380
25	Mississippi	153	2205	1519	23190
26	Missouri	863	6829	2731	87200
27	Montana	136	1142	247	11390
28	Nebraska	239	2351	710	31720
29	Nevada	472	1179	579	23980
30	New Hampshire	657	1862	1664	24350
31	New Jersey	3629	9784	12795	165150
32	New Mexico	354	4704	4977	33500
33	New York	6407	29415	13031	272930
34	North Carolina	2233	12845	6343	135380
35	North Dakota	77	768	382	8420
36	Ohio	3295	13913	8583	180360
37	Oklahoma	584	2416	968	*47747*
38	Oregon	2536	4658	3572	62570
39	Pennsylvania	3191	20229	9944	195730
40	Rhode Island	354	2166	1757	19660
41	South Carolina	691	3980	1616	51030
42	South Dakota	79	440	149	9420
43	Tennessee	817	6913	2998	65120
44	Texas	6717	21885	14785	383180
45	Utah	800	3659	1506	43030
46	Vermont	486	1040	492	11770
47	Virginia	1232	8396	7582	220180
48	Washington	3620	12677	11469	154610
49	West Virginia	111	1195	538	16100
50	Wisconsin	2151	6683	3642	95230
51	Wyoming	56	538	113	6760

PAT indicates Patents Granted for the year 2006 (USPTO)

PUB indicates Scientific Publications for the year 2006 (Science Citation Index Expanded Database)

EXP indicates R&D Expenditure for the year 2003 (National Science Foundation. Arlington, VA)

PER indicates Personnel in Science and Engineering Occupations for the year 2004 (National Science Board, Arlington, VA)