Analyzing R&D Efficiency in Asia and the OECD: An Application of the Malmquist Productivity Index

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Abstract— **In recent years, there has been a growing interest in R&D efficiency among scholars and policy makers across the world. Several Asian countries have shown remarkable progress in R&D efficiency which seems to be at the cost of the leading nations like USA and the UK. This study investigates R&D efficiency in 22 countries, 20 of them members of the OECD, and the Russian Federation and China. The analysis is carried out using the Malmquist Productivity Index for the periods 2002-04 and 2004-06. The R&D inputs taken are gross domestic expenditure on R&D and the number of full-time researchers per million population. The outputs taken are patents granted to residents and the number of scientific publications indexed in the Science Citation Index. We find that China exhibits a rapid increase in number of scientific publications while the Republic of Korea shows exemplary performance in patenting among residents in recent years. Thus we confirm the results of some earlier studies, and contribute mainly by investigating R&D efficiencies using the MPI which is especially useful in comparing productivity in multiple decision making units over periods of time, and examining reasons for the efficiencies of China and the Republic of Korea. The results indicate significant improvements in technical capabilities of the residents of China and the Republic of Korea.**

Keywords- Asia, DEA, Malmquist Productivity Index, OECD, Patents, R&D Efficiency

I. INTRODUCTION

Patents are widely acknowledged as important indicators of the technological progress of nations. While patenting has a long history, it has been recognized as an indicator of technological progress relatively recently. Based on the pioneering work of Schmookler [1] and later on Griliches [2], the importance of patents and patenting came to be recognized by academics, policy makers and the industry, though not necessarily in that order. Patents are outputs of the R&D process, which moved from the small labs of individual inventors to the vast organized R&D labs of industries and governments. The shift from individual research to organized teams dedicated towards specific goals greatly improved the productivity of these labs and lead to more efficient use of R&D resources. This trend was initially noticed in the German chemical industry in the latter part of the nineteenth century and the early twentieth century. As research productivity increased, this organizational improvement was used by the other developed countries of the time to enhance their own technological capabilities an example of which was the Manhattan project. Another significant development was the creation of links between academia and government and later on industry, which also played a major role in improving research productivity and outcomes. This tendency to collaborate continued even after the war and research has acknowledged the benefits of collaboration on research productivity and outcomes. This stream of research on collaboration has moved from strength to strength, focusing on increasingly reliable indicators though there is still a long way to go. As a result of the success of collaboration and in recognition of critical role played by R&D in economic growth, there has been a sustained effort by many countries to stimulate and sustain R&D in their countries.

The USA, Japan and members of the European Union have been competing over the years to demonstrate their technological superiority. This has lead to discussions on the decline in British Science (e.g., [3], [4], [5], [6], and [7]) in the eighties and nineties, and the more recent identification of the European Paradox (e.g., [8] and [9]). The European paradox highlights the inability of the members of the European Union to capitalize on their leadership in scientific publications, and convert it to a larger number of patents and market leadership. The USA has been the leader in this sphere and is closely followed by Japan.

Lately, the decline in world shares of patents and publications of the USA and members of the European Union has come to the attention of scholars (e.g., [10], [11] and [12]). This decline is mainly attributed to the increasing scientific activity of a group of Asian nations mainly China and South Korea. A number of scholars and institutions have commented on the rise of these Asian nations (e.g., [13], [14], [15], [16], [17] and [18]). This study seeks to contribute to the ongoing discussion on this select group of Asian nations by analyzing trends in their research productivity using the Malmquist Productivity Index (MPI).

This paper is organized as follows. Section II provides a brief overview of the relevant literature. The methodology used and the sources of the data are described in Section III. Section IV presents the results followed by a conclusion in Section V.

II. LITERATURE REVIEW

A. *Patents, R&D Efficiency and Economic Growth*

R&D has been acknowledged as one of the major drivers of economic growth. Equitable economic growth has the ability to improve the standard of living of the citizens of the country. Developed nations are hampered by low levels of economic growth while developing nations are challenged by the problems of stimulating and sustaining economic growth. Economic growth is thus viewed as the panacea for the various ills faced by both developed and developing countries. The relationship between R&D and economic growth is not a new one but has been a subject of scrutiny for over a century now. Friedrich List [19] conceptualized the role of R&D in economic growth and inspired "tech-nationalism" in the German nation. This was primarily in order to follow and overtake the success of the British Empire which was the most economically powerful nation of the period. Later on, this concept was further elaborated by Schumpeter (e.g., [20] and [21]) in his writings on R&D, innovations and entrepreneurs. Interest in R&D was further awakened by the path breaking paper of Solow [22], who identified the role of technical change in economic growth. Empirical studies by Comanor and Scherer [23], and theoretical contributions by Lucas [24], Romer [25] and Segerstrom [26] formalized the role of technological change in economic growth. Kline and Rosenberg [27] also cemented the understanding that R&D and economic growth had a linear relationship. This understanding was later developed into a systemic view of innovation and R&D in light of empirical studies like the SAPPHO project [28]. The term "National System of Innovation" came in to existence (e.g., [29] and [30]) and an immense number of papers on this concept emerged in a comparatively short period of about 20 years. This is a testament to its relevance and interest to both academics and policy makers. As innovation and R&D have strong relevance for firms, institutions, regions, sectors and nations, a large body of research has developed to look at innovation and R&D from these different perspectives. This has lead to the development of studies of innovation at the level of the firm [31], institutions [32], Regional Innovation Systems [33], Sectoral Systems [34] and Technological Systems [35].

Of late, scholars have observed the increasing numbers of patents and scientific publications emanating from the Asian region, particularly China and South Korea. Several papers have looked at this phenomenon from different perspectives in different fields of study [36]. Some have focused solely on publications (e.g., [37], [38] and [39]) and some solely on patent outputs (e.g., [40] and [41]). A few studies are comparative in nature but consider only a few countries (e.g., [42], [43] and [44]). Some studies look at the role of collaboration and linkages [45], and the others focus only on specific sectors of the economy (e.g., [46] and [47]). As the R&D process has been conceptualized as a knowledge generating process with multiple inputs and outputs, it is possible to apply the concept of Data Envelopment Analysis (DEA) and its panel data form, the Malmquist Productivity Index which assesses changes in productivity of decision making units over periods in time. We present a brief overview of the studies on R&D efficiency across nations

B. *Comparative Studies of R&D Efficiency across Nations*

There are only a limited number of studies on R&D efficiency across nations. Teitel [48] compared 68 countries using a log-linear form of the production function. He took the number of patents granted to residents as a dependent variable and number of researchers, R&D expenditure, per capita income and population as explanatory variables. He concluded that the simple production function model did not yield very useful results because of multicollinearity between the explanatory variables. Rousseau and Rousseau [49] used DEA to assess the R&D efficiency of various countries using constant returns to scale (CRS) formulation. They analyzed 18 developed countries and highlighted methodological problems like the language bias in the ISI publications data and the fact that there could be problems due to taking patent data from the European Patent Office (EPO). Extending their work [50] for developed countries from Western Europe and later on adding some non European countries, they found that Switzerland was the most efficient country in 1993 followed by the Netherlands. Lee and Park [51] have performed a CRS DEA study on 27 countries and have concluded that Asian countries in general are inefficient in R&D. While discussing areas for further research, they mention the need to take the variable returns to scale (VRS) formulation. Wang and Huang [52] analyze R&D efficiency in 30 OECD and non-OECD countries also taking into account environmental factors such as knowledge of English language. They find that a large portion of the inefficiency can be explained by a country's English proficiency indicator. Sharma and Thomas [53] have conducted a study on R&D efficiency on a group of 22 developed and developing countries using both CRS and VRS formulations and concluded that some Asian countries are highly efficient and other countries have to learn from them. While each of these studies has its own merit, they are basically cross sectional in nature at a particular point in time. Existing studies on R&D efficiency have either failed to use the concept of time lags between inputs and outputs (e.g., [49] and [50]) or have compared relative R&D efficiency of countries using CRS or VRS formulations (e.g., [51], [52] and [53]). No study has compared a set of countries on R&D efficiency using the Malmquist productivity index (MPI) to the best of our knowledge.

As DEA has a provision to study variations in relative efficiency of decision making units over periods of time called the Malmquist Productivity Index, and the fact that longitudinal data on a few of the R&D inputs and outputs are available for these Asian countries motivates us to undertake a Malmquist DEA study to assess the relative R&D efficiency of these nations. This study will contribute to the ongoing discussion of the improvements in R&D efficiency across countries in a comparative framework.

III. METHODOLOGY AND DATA

A. DEA and the Malmquist Productivity Index(MPI)

Data envelopment analysis (DEA) is an important non-parametric analysis technique which has found wide applicability in several fields of study. This technique has its origins in the seminal paper by Farell [54] where he discusses the problems in measuring productive efficiency. The DEA technique was initially developed by Charnes et. al. [55] and Banker et. al. [56] later on improved on the initial constant returns to scale model by introducing an additional constraint which led to its applicability in a variable returns to scale framework. This ingenious improvement has led to increased acceptance of this technique across a wide variety of fields. For an overview of the methodological developments in DEA the reader is referred to Wade and Seiford [57].

There have been a large number of studies in the banking industry, initially in the developed countries using DEA [58] and later on this technique has diffused to the developing countries [59]. Another favourite area of application is in analyzing the efficiency of hospitals [60]. Other applications include the automotive components industry in India [61], internet companies [62], vendor evaluation [63], network efficiency of OECD countries [64], football teams [65], university libraries [66], paper mills [67], higher education [68] and traffic safety [69]. This technique has also found application in evaluation of engineering design projects [70], knowledge worker performance analysis [71], software team efficiency and productivity [72] and productivity changes in thermal power plants [73]. The large number of areas in which DEA has been applied is an indicator of its relevance and applicability in different contexts [74].

DEA deals with measuring the relative efficiency of decision making units in a constant returns to scale as well as a variable returns to scale framework. Data is collected on the inputs and outputs to a production process for different decision making units (DMUs) which have to be compared. The technique is non parametric and helps in the creation of the frontier of efficient performance based on the actual performance of the decision making units. The DMUs falling on the frontier are termed to be efficient while those away from the frontier are termed to be inefficient. The efficient DMUs achieve a score of 1.00 which is an indicator of efficient performance. A score less than 1.00 shows inefficiency which needs to be addressed. This technique can also be used on longitudinal data using the Malmquist productivity index. The development of the frontier can be for both constant returns to scale (CRS) and the variable returns to scale (VRS). The DEA can be input oriented or output oriented based on the need to either focus on input reduction while maintaining output at current levels, or increasing outputs keeping inputs at current levels.

Literature affirms the assumption that most firms operate with variable returns to scale rather than constant returns to scale, hence it is considered practical to present CRS as well as VRS results to add richness of the analysis. While the basic DEA models use CRS and VRS formulations, they are static in time, hence leading to the criticism that this is a case of comparing statics. This criticism can be ameliorated by using longitudinal data and the Malmquist productivity index (MPI).

The Malmquist productivity index (MPI) measures the productivity changes in a DMU between two time periods. It requires panel data on inputs and outputs, and the analysis provides values for total factor productivity (TFP). The output based Malmquist index is defines as the product of the technical change or "technology (T)" and the technical efficiency (E). The technology (T) can be understood to be shifts in the efficiency frontier, while the technical efficiency (E) can be understood as the movement or catch up of the DMU towards the efficiency frontier in a particular time period.

$$M = T \times E \tag{1}$$

Or

MPI = Technology change (T) x Technical efficiency change (E)

More formally, following [75]

$$M^{t+1}(x^{t+1}, y^{t+1}, x^t, y^t) = \left[\frac{D^t(x^{t+1}, y^{t+1})}{D^t(x^t, y^t)} \times \frac{D^{t+1}(x^{t+1}, y^{t+1})}{D^{t+1}(x^t, y^t)}\right]^{1/2} \tag{2}$$

where D^t is a Distance Function and measures the efficiency of the conversion of inputs x^t to outputs y^t during the period t. For an elegant discussion of this concept, the reader is referred to the standard text [76, pp.328].

The Malmquist productivity index can be decomposed into two components, the shifts in the efficiency frontier which indicate improvements in "technology (T)" and the movement of the DMU towards the frontier and called "technical efficiency (E)".

$$M^{t+1}(x^{t+1}, y^{t+1}, x^t, y^t) = \frac{D^{t+1}(x^{t+1}, y^{t+1})}{D^t(x^t, y^t)}\left[\frac{D^t(x^{t+1}, y^{t+1})}{D^{t+1}(x^{t+1}, y^{t+1})} \times \frac{D^t(x^t, y^t)}{D^{t+1}(x^t, y^t)}\right]^{1/2} \tag{3}$$

Values more than one for the Malmquist Productivity Index indicate improvements in total factor productivity over the previous time period, and values less than one indicate a reversal in productivity. Ramanathan [77] has suggested that when DEA and MPI are applied to compare countries, the improvements in the MPI should be interpreted as improvements in "changes in social institutions". This seems a valid suggestion and thus the MPI can denote the improvements in the ability to do research and can indicate the improvements in the supporting infrastructure.

B. Data Sources

Following existing literature (e.g. [49], [50], [51] and [52]), this study uses gross domestic expenditure on research and development (GERD)[1] measured in Purchasing Power Parity (PPP)[2] Million $, and the number of Researchers[3] as R&D inputs for a total of 22 countries. The inputs are lagged by 3 years as compared to the outputs following [2] and [18, pp. 49]. Thus the data on the inputs are for the years 1999, 2001 and 2003 while the data for the outputs are for 2002, 2004 and 2006 respectively. These countries are predominantly from the OECD, except for the Russian Federation and China. Attempts were made to do a comparative study of the OECD countries and the BRIC countries, but the study had to be finally restricted to some 20 OECD countries, the Russian federation and China due to lack of data on all the variables under consideration. In this study, the number of researchers is measured in Full Time Equivalent (FTE) per million population of the country. The data on these inputs are taken from UNESCO Institute for Statistics. The patents granted to residents are taken as an output and an indicator of the R&D capabilities of the country and is collected from the World Intellectual Property Organization, WIPO. The data on scientific publications are taken from the Science Citation Index (SCI) as the academic outputs of the R&D process of the country. This data on the number of scientific publications is taken from the ISI Web of Science Online Database taking articles, letters, notes and reviews as publications following [78]. The data is analyzed using the DEAP 2.1 software [79].

IV. RESULTS

This study used data on a total of 22 countries, 20 from the OECD and the Russian federation and China for the years 2002, 2004 and 2006. The motivation for this sample of countries is the analysis of current trends by researchers (e.g. [10]-[15]) which indicate the emergence of several Asian nations on the R&D efficiency frontier, and the concomitant decline in world shares of R&D outputs of several OECD members. The analysis is done using the Malmquist Productivity Index (MPI) and the results are presented in Table I.

TABLE I
EFFICIENCY CHANGES OVER THE PERIOD 2002-04

S. No.	Country	Malmquist Productivity Index (M)	Technical Efficiency (E)	Technology (T)	VRS Technical Efficiency	Scale Efficiency
1	Canada	0.858	0.719	1.193	0.902	0.797
2	Czech Republic	0.961	0.879	1.094	0.897	0.980
3	Denmark	0.912	0.879	1.037	0.877	1.003
4	Finland	0.896	0.947	0.946	0.915	1.035
5	France	0.959	0.826	1.160	0.983	0.841
6	Germany	0.964	0.816	1.181	0.998	0.817
7	Hungary	0.714	0.728	0.980	0.780	0.934
8	Iceland	0.836	0.882	0.948	1.000	0.882
9	Ireland	1.007	1.043	0.965	1.027	1.016
10	Japan	0.984	1.000	0.984	1.000	1.000
11	Rep. of Korea	0.882	1.000	0.882	1.000	1.000
12	Netherlands	1.029	0.912	1.129	1.078	0.845
13	Poland	1.123	1.000	1.123	1.000	1.000
14	Portugal	1.048	1.039	1.008	1.006	1.033
15	Slovak Rep.	1.007	1.063	0.948	1.000	1.063
16	Spain	0.943	0.801	1.177	0.972	0.824
17	Sweden	0.814	0.778	1.047	0.876	0.887
18	Turkey	1.271	1.000	1.271	1.000	1.000
19	UK	0.988	0.787	1.255	1.000	0.787
20	USA	1.039	0.924	1.124	1.000	0.924
21	Russian Fed.	0.816	0.903	0.903	0.990	0.912
22	China	1.234	1.000	1.234	1.000	1.000
	G. M.	***0.959***	***0.900***	***1.066***	***0.966***	***0.931***
	S. D.	***0.131***	***0.105***	***0.119***	***0.066***	***0.087***

Ireland, the Netherlands, Poland, Portugal, the Slovak Republic, Turkey, USA and China show improvements in the Malmquist Productivity Index (MPI) for this period mostly due to technology change. What needs to be assessed further is whether this change or improvement in technology is temporary or shows a continuing trend. We continue the analysis by calculating the MPI for the period 2004-06 in Table II.

[1] **Gross domestic expenditure on R&D (GERD)** is the total intramural expenditure on R&D performed on the national territory during a given period.

[2] **Purchasing power parities (PPP)** is a rate of currency conversion into US dollars that eliminates the differences in price levels among countries.

[3] **Researchers** are professionals engaged in the conception or creation of new knowledge, products, processes, methods and systems, and in the planning and management of R&D projects. Postgraduate students at the PhD level (ISCED level 6) engaged in R&D are also considered as researchers.

Table II
EFFICIENCY CHANGES OVER THE PERIOD 2004-06

S. No	Country	Malmquist Productivity Index (M)	Technical Efficiency (E)	Technology (T)	VRS Technical Efficiency	Scale Efficiency
1	Canada	1.155	0.956	1.209	1.104	0.865
2	Czech Rep.	1.062	0.892	1.191	0.876	1.018
3	Denmark	0.986	0.828	1.191	0.910	0.910
4	Finland	0.894	0.700	1.277	0.866	0.808
5	France	1.068	0.939	1.136	0.967	0.972
6	Germany	1.090	1.011	1.078	0.974	1.038
7	Hungary	0.991	0.832	1.191	0.812	1.025
8	Iceland	1.150	0.966	1.191	1.000	0.966
9	Ireland	0.991	0.828	1.196	0.818	1.013
10	Japan	1.114	0.795	1.400	1.000	0.795
11	Rep. of Korea	1.999	1.000	1.999	1.000	1.000
12	Netherlands	1.140	0.919	1.241	1.032	0.891
13	Poland	1.209	1.000	1.209	1.000	1.000
14	Portugal	1.398	1.174	1.191	1.190	0.987
15	Slovak Rep.	1.079	0.906	1.191	1.000	0.906
16	Spain	0.968	0.788	1.229	0.941	0.837
17	Sweden	0.959	0.766	1.251	0.935	0.820
18	Turkey	1.056	1.000	1.056	1.000	1.000
19	UK	1.027	1.059	0.970	1.000	1.059
20	USA	1.101	0.899	1.225	1.000	0.899
21	Russian Fed.	0.761	0.464	1.641	0.551	0.842
22	China	1.209	1.000	1.209	1.000	1.000
	G. M.	***1.090***	***0.883***	***1.235***	***0.944***	***0.935***
	S. D.	***0.236***	***0.146***	***0.210***	***0.124***	***0.083***

From Table II, we can see that 15 out of the 22 countries studied are showing improvements in MPI in this period. The Netherlands, Poland, Portugal, the Slovak Republic, Turkey, USA and China show improvements in their MPI in both the time periods. The highest MPI of 1.999 is secured by the Republic of Korea in 2004-06. Except for the United Kingdom (UK), all the countries in the sample show a score of more than one on technology change (T) for the period 2004-06 indicating a possible deceleration in R&D activity. A closer look at Table II reveals that most of the countries have high values on the MPI mainly due to their improvements in technology change (T). To put the change in MPI and technical efficiencies in a better perspective, we allot ranks to each country for both the periods based on their performance on the MPI. The results are presented in Table III.

TABLE III
RANKS BASED ON MALMQUIST PRODUCTIVITY INDEX

Country	**2002-04**	**2004-06**
Canada	18	5
Czech Rep.	12	13
Denmark	15	18
Finland	16	21
France	13	12
Germany	11	10
Hungary	22	16
Iceland	19	6
Ireland	7	17
Japan	10	8
Rep. of Korea	17	1
Netherlands	6	7
Poland	3	3
Portugal	4	2
Slovak Rep.	8	11
Spain	14	19
Sweden	21	20
Turkey	1	14
UK	9	15
USA	5	9
Russian Fed.	20	22
China	2	4

We can see that several countries show a marked improvement in their performance based on the MPI scores. These countries are Canada, Iceland and the Republic of Korea. Each of these countries needs to be further investigated to assess their overall performance and reasons for the same. Analysis of Iceland reveals that its MPI scores are affected by an increase in the number of patents granted to residents during the periods under study. Iceland has been included in the sample mainly because it has a large number of researchers, thus leading to the expectation of reasonable output. The MPI scores it gets are mainly due to an increase in the number of patents which though minimal in absolute terms are high when compared to its performance in the past time period. Thus, we concentrate our efforts on understanding the reasons for the performance of Canada and the Republic of Korea. The trends in R&D inputs and outputs for Canada for the period 1997-2006 are presented in Fig. 1.

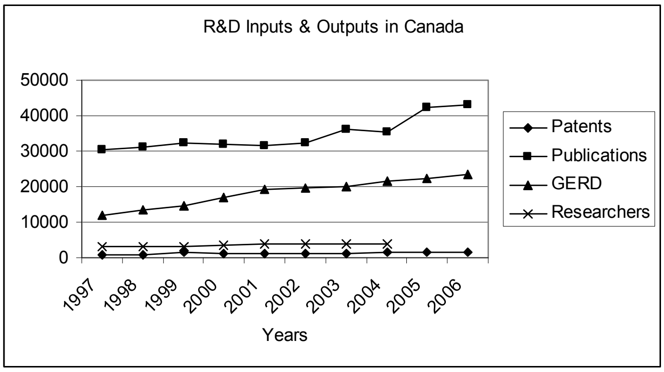

Fig. 1. R&D Inputs and Outputs in Canada (1997-2006)

We can explain the improvement in the MPI performance of Canada due to the noticeable increase the number of scientific publication in the Science Citation Index during the period 2004-06. This is a significant achievement because it has been achieved without major increases in the R&D inputs GERD and Researchers. Thus, the MPI has acknowledged the improvements in technology which has lead to this increase in scientific publication output from Canada. To further compare this increase in scientific publication output, we compare the scientific publication output of a few Asian nations for the time period 1997-2005. The results are presented in Fig. 2.

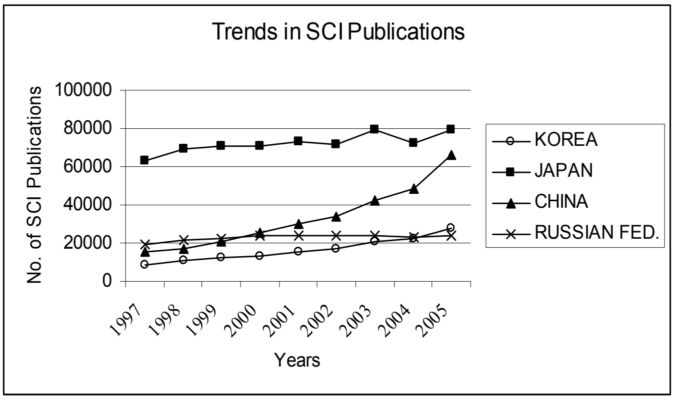

Fig. 2. Trends in SCI Publications for selected Asian countries (1997-2005)

We compare the scientific publication output of the Republic of Korea, Japan, China and the Russian Federation based on data collected from the ISI Web of Science database. It is evident that there is a rapid increase in number of scientific publications emerging from China. This is perhaps one of the significant reasons for the falling world shares of scientific publications which have been noticed by other researchers (e.g., [10]-[18]). As we see a more modest increase from the Republic of Korea, it seems necessary to further assess the performance of these four Asian nations on the number of patents granted to residents. Using data collected from the World Intellectual Property Organization (WIPO) over the period 1992-2006 on the number of patents granted to residents, we can observe the trends in this R&D output. The results are presented in Fig. 3.

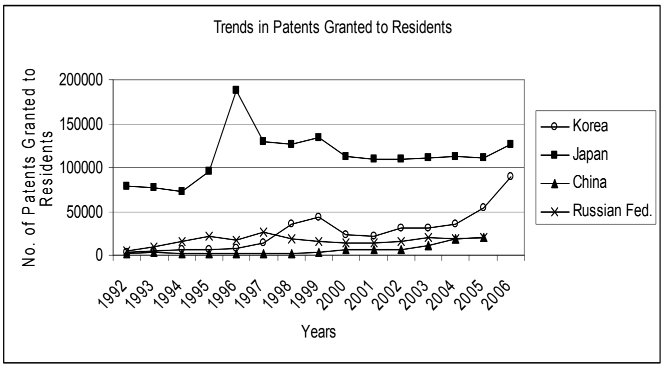

Fig. 3. Trends in Patents Granted to Residents for selected Asian countries (1992-2006)

It is evident that the Republic of Korea has shown a massive increase in the number of patents granted to residents, especially during the period 2004-06, which is the primary reason for achieving the highest score in the MPI for that period among the selected countries. Thus we are able to confirm that the MPI is a robust measure of productivity and analyses incorporating this technique should also investigate the reasons for improved performance on this index when data permits further longitudinal analysis of inputs and outputs.

V. CONCLUSIONS

Scholars have been interested in the R&D efficiency of nations for several years now. While existing studies have looked at R&D efficiency across nations at particular points in time, no research has investigated the changes in R&D efficiency in consecutive time periods. With nations competing to increase and sustain the technological edge over others, it is imperative to identify the nations which are currently leading the race for R&D efficiency and the reasons for their success. This study uses the Malmquist Productivity Index (MPI) on a group of 22 nations, 20 of which are members of the OECD, and the Russian Federation and China, in an attempt to assess their R&D efficiencies over the periods 2002-04 and 2004-06. The inputs to the R&D process are gross domestic expenditure on R&D (GERD) and the total number of full-time researchers. The outputs taken are patents granted to residents and number of scientific publications indexed in the database ISI web of science. Results confirm the rapid advancement of China and the Republic of Korea, which is leading to reduced world shares of scientific publication and patents granted to residents of major scientific nations like the USA and the UK. Further analysis of the reasons for high MPI scores reveals that China exhibits rapid increase in the number of scientific publications while the Republic of Korea shows exceptional growth in patenting among its residents. This study contributes to the existing literature by assessing R&D efficiency in a longitudinal perspective by using the Malmquist Productivity Index and by identifying that China's performance on the MPI is mainly due to scientific publication output. The Republic of Korea shows sustained increases in patenting among residents mainly due to the progressive policies followed by the Korean government over several decades (e.g., [80] and [81]).

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