

The Albuquerque model and efficiency indicators in national scientific productivity with respect to manpower and funding in science

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Abstract Due to recession in the world economy there is a trend towards a reduction in growth of R&D expenditure in the G7 countries. At the same time countries like China and Korea are investing more in scientific research. We compare the differences in the inputs to science for different countries and explore the level of *efficiency* in the output of scientific papers with respect to inputs such as manpower and investment. We find that the EU countries are relatively more efficient than Japan, the USA and also China and Korea so far as the production of papers is concerned. However, if efficiency is considered in terms of patents, Japan Korea and the USA are ahead. We compare our results with Albuquerque's model linking patent to paper ratios and development, and find significant deviations for some countries. We deduce that there has been a shift from publishing towards patenting in certain countries and link it to high contribution from the business sector to R&D expenditure. Preliminary results of this analysis have been presented in Basu (In Proceedings of the 14th International Society for Scientometrics and Informetrics (ISSI) Conference, 2013).

Keywords Patents · R&D efficiency · GERD · BERD · Albuquerque model · Indicators

Introduction

While there is a slowing down or recession across the globe, there is also evidence of Asian countries that have significantly increased their share of investment in R&D in the same period. In terms of output, China has substantially increased its output of scientific papers such that now it is second only to the United States in the production of papers. In terms of

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manpower it is second to the United States and may soon cross those figures, though some of the manpower statistics may not be entirely accurate. Korea has also substantially increased its R&D investment as a share of GDP.

Investment on R&D is a correlate of development. Developed countries have higher Gross Expenditure on R&D (GERD) shares as compared to GDP shares, the GERD being taken as the expenditure on the creation of new knowledge (Hollanders and Soete 2010). This helps us identify countries that have increased R&D expenditures, such that *GERD share/GDP share* tends to or exceeds unity. How does increased investment of resources translate into outputs? Do developed countries make more efficient use of their resources? The question of efficiency of scientific productivity at the national level has been considered earlier by several authors (May 1997; Rousseau and Rousseau 1998; King 2004; Vinkler 2005, 2008; Shelton 2008; Leydesdorff and Wagner 2009; Wendt et al. 2012), who also point out difficulties in making cross-national comparisons. Primarily they have dealt with publications and citations in comparison to research expenditure or GNP and have considered European countries, the US and Japan or China. Rousseau has considered both publications and patents. In this study we look at the output of both scientific papers and patents for a selected set of countries from all the continents, and link it to development following a model by Albuquerque (2005) which is detailed below. Publications are taken as an indicator of scientific health, and patents as an indicator of innovative activity for a country.

Albuquerque proposed a simple model that linked output indicators to development. He showed that the paper production and patent production ratio changes as countries become more developed. He termed this as technological ‘maturity’ and took the ratio of papers to patents, normalized by population, as an indicator of ‘efficiency’. The ratio decreases as a function of development. He also showed that less developed countries fall on a line separated by a threshold from developed countries, the latter falling on a line of higher slope when patents are plotted against papers, both normalized by population (Fig. 1).

We will build on Albuquerque’s approach, but with altered definitions of efficiency. An informal definition of efficiency could be the use made of resources in the attainment of goals (Rousseau and Rousseau 1998). Accordingly, we have taken definitions of efficiency of the science system as the output of papers and patents with respect to input resources, manpower in R&D and expenditure. This must be distinguished from Albuquerque’s definition. Our definition more closely captures the efficiency with respect to actual expenditure and manpower in R&D. We have two dimensions for the outputs, patents and papers, and two dimensions for the inputs, research expenditure and manpower, leading to a total of 4 indicators of efficiency. Using these indicators we locate the positions of different countries along different dimensions of efficiency.

Data and methodology

Data on scientific papers and patents is taken from the SCI-Expanded and USPTO for the years 2008 and 2007. Restricting to the USPTO, the United States Patent Office gives a bias in favour of the USA. Ideally some of the other major patent databases should be included in the analysis. However for this preliminary study we only consider the USPTO.

The Gross Domestic Product GDP and Gross Expenditure on Research and Development GERD are both adjusted to purchasing power parity (PPP) and compared for selected countries for the years 2002 and 2007. This is done in order to make local investments comparable across countries. Data is obtained from the UNESCO Science Report (2010).

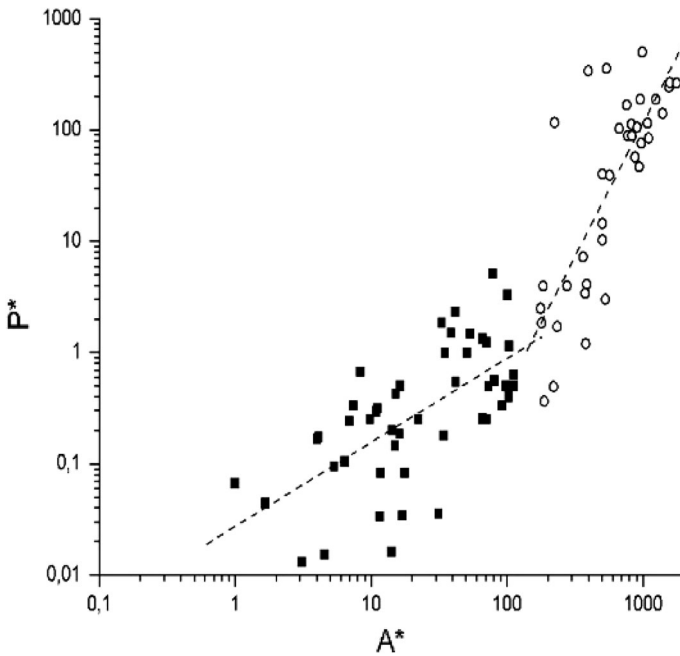


Fig. 1 Papers A^* and Patents P^* (per mill. inhabitants) plotted for less developed countries (*squares*) and developed countries (*open circles*). (From Albuquerque 2005)

Countries with increasing GERD share as compared to GDP shares, which are investing more in R&D, are identified in terms of change in *GERD share/GDP share*.

Efficiency is defined in terms of inputs, namely expenditure and manpower in research, and outputs, namely papers and patents. Manpower is measured in terms of full time equivalents (FTEs) engaged in R&D.

The efficiency for paper production has two values $EE(Pap)$ and $ME(Pap)$,

$$\text{Expenditure efficiency } EE(Pap) = \text{papers}/GERD \tag{1}$$

$$\text{Manpower efficiency } ME(Pap) = \text{papers}/\text{manpower} \tag{2}$$

The efficiency for patent production also has two values $EE(Pat)$ and $ME(Pat)$,

$$\text{Patent expenditure efficiency } EE(Pat) = \text{patents}/GERD \tag{3}$$

$$\text{Patent manpower efficiency } ME(Pat) = \text{patents}/\text{manpower} \tag{4}$$

Analysis

Recent changes in GERD indicate the countries that are investing more (or less) in R&D. We first identify the countries for which R&D Expenditure is increasing in relation to their GDP (Table 1). Columns 1–4 show the base data of shares of GDP and GERD for different countries (UNESCO World Report).

Columns (5) and (6) show ratio of GERD share to GDP share. Countries with ratio >1 have a higher share of GERD than GDP, and may be taken as developed countries. In this

Table 1 GERD and GDP shares of selected countries

Country	(1) GDP share 2002	(2) GDP share 2007	(3) GERD share 2002	(4) GERD share 2007	(5) GERD share/GDP share 2002	(6) GERD share/GDP share 2007	(7) GERD share/GDP share 2007–2002
EU	25.3	22.5	26.1	23.1	1.03	1.03	0.00
USA	22.5	20.7	35.1	32.6	1.56	1.57	0.01
China	7.9	10.7	5	8.9	0.63	0.83	0.20
Japan	7.4	6.5	13.7	12.9	1.85	1.98	0.13
Germany	4.9	4.3	7.2	6.3	1.47	1.47	0.00
India	3.8	4.7	1.6	2.2	0.42	0.47	0.05
France	3.7	3.1	3.9	3.4	1.05	1.10	0.04
UK	3.7	3.2	3.9	3.4	1.05	1.06	0.01
Italy	3.3	2.8	2.2	1.9	0.67	0.68	0.01
Brazil	2.9	2.8	1.6	1.8	0.55	0.64	0.09
Russia	2.8	3.2	2.0	2.0	0.71	0.63	−0.09
Mexico	2.1	2.3	0.5	0.5	0.24	0.22	−0.02
Korea	2.0	1.9	2.8	3.6	1.40	1.89	0.49
Canada	2.0	1.9	2.4	2.1	1.20	1.11	−0.09
Australia	1.3	1.2	1.3	1.4	1.00	1.17	0.17

case the countries are Japan, USA, Germany, UK, France, Korea, Canada and Australia. Other countries Mexico, Russia, Brazil, India, China and Italy have a lower world share of GERD as compared to GDP. Between 2002 and 2007 countries that have made changes to share of GERD to share of GDP are seen in column (7). Countries that have made the largest increases are Korea, China, Japan and Australia. Countries for which the GERD/GDP ratio has fallen are Russia, Mexico and Canada.

Next we look at the expenditure efficiency EE and manpower efficiency ME for the list of selected countries. Table 2 shows the manpower and GERD figures (in FTE's and billion \$ PPP) together with the output of papers in the science citation index-E using fractional counts, and patents in the USPTO.

Expenditure and manpower efficiency for papers are calculated (Eqs. 1 and 2) and plotted in Fig. 2. In Fig. 2, we see that Italy has the highest values for expenditure efficiency EE(Pap) and manpower efficiency ME(Pap) in the production of scientific papers. The European Union countries all lie above average along both directions of efficiency, except Germany which is slightly below average in expenditure efficiency. Australia and Canada lie alongside the EU countries at about the same level of expenditure efficiency but slightly better on manpower efficiency. Japan, China, Korea, Russia and the United States are below average on both counts EE and ME. Among them Russia is about average in EE, but well below average on ME. USA is slightly below average on manpower efficiency, but well below average on expenditure efficiency. Brazil and India are both near average with India slightly above average on both counts and Brazil slightly below average on manpower efficiency ME. Mexico is average on manpower efficiency but well below average on expenditure efficiency EE.

The unexpectedly low values of efficiency in terms of paper output are surprising for Japan, the USA as these along with Korea and Germany are also the countries that have shown an increase in the GERD/GDP ratio as seen from Table 1. It has been suggested, for

Table 2 Manpower, GERD, papers and patents for selected countries

	GERD \$bnPPP	Manpower (FTE's)	Papers SCI-E	Patents USPTO
Australia	15.36	87,140	28,313	1,516
Brazil	20.20	133,266	26,482	124
Canada	23.96	139,011	43,539	3,806
China	102.40	14,23,380	104,968	7,362
France	42.89	215,755	57,133	3,631
Germany	72.24	290,853	76,368	9,713
India	24.79	154,827	36,261	741
Italy	22.12	96,303	45,273	1,836
Japan	147.90	709,974	74,618	33,572
Korea	41.30	221,928	32,781	6,424
Mexico	55.90	37,930	82,62	81
Russia	23.40	451,213	27,083	286
Spain	19.34	130,896	35,739	363
UK	41.04	261,406	71,302	4,007
USA	398.00	14,25,550	27,2879	81,811

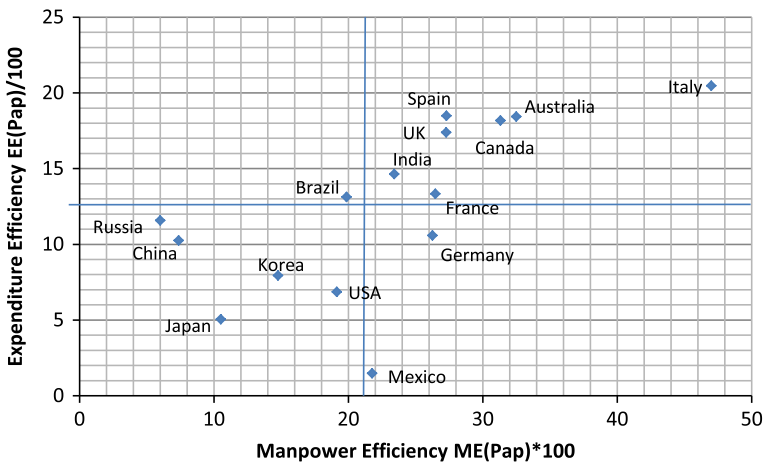


Fig. 2 Efficiency in the production of papers with respect to manpower and expenditure showing Italy has the highest efficiency for the production of papers

example, by Vinkler (2008) that rich countries spend more and poorer countries less for the same goals. It was also shown by Foland and Shelton (2010) that lowered efficiency is not an artefact of the data but depends significantly on shifts between different sectors of expenditure, such as civil, military or higher education. We will return to this point later.

It remains to look at patents, which constitute the other dimension of R&D production. Data on patents is given in Table 2. Patent manpower efficiency ME(Pat) is calculated using Eqs. 3 and 4, and plotted in Fig. 3 against the manpower efficiency of papers ME(Pap). This would be the analogue of Albuquerque’s model with our definition of efficiency.

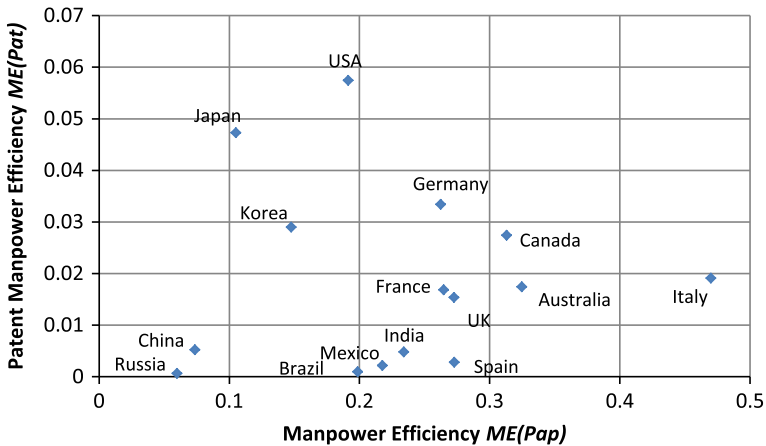


Fig. 3 Efficiency in the production of patents with respect to manpower ME(Pat) versus efficiency in the production of papers ME(Pap) with respect to manpower

From Fig. 3 we see that patent manpower efficiency is high for the USA followed by Japan, Germany and Korea. For China and Russia this efficiency is low due to high values of manpower. The European countries are at an intermediate level, while Mexico, Brazil, Spain and India are at low levels of patenting efficiency with respect to manpower due to very low levels of patenting. If we compare this curve to Albuquerque, we note the four countries that stand away from the distribution of developed countries on the right, namely Japan, USA, Korea and Germany. They deviate from Albuquerque's simple model (Fig. 1) where higher patent efficiency is linked to higher paper efficiency.

While Fig. 3 is the analogue of the Albuquerque model with R&D manpower used in place of population, we recognize that manpower values can have large inaccuracies due to problems with harmonizing data across OECD definitions. This is especially true in the case of certain countries like China. Foland and Shelton (2010) have also shown that expenditure has higher significance than labour in the regression of output of papers to expenditure and labour. So, instead of using manpower we use expenditure to define efficiency, plotting the patent expenditure efficiency in Fig. 4 EE(Pat) (Eq. 3) against the expenditure efficiency EE(Pap) (Eq. 1).

Patent Efficiency with respect to R&D expenditure is the highest for Japan followed by USA, Canada, Korea and Germany. China's Patent efficiency with respect to R&D expenditure is at a medium level just below the remaining European countries, while with respect to manpower efficiency it had been low (Fig. 3). Australia, Italy France are at a medium level of patenting efficiency, while India, Brazil, Russia and Spain are at a low level of efficiency for patenting but at a medium level for papers.

Note in Fig. 4, countries with the highest patent efficiencies with respect to expenditure, namely Japan, USA, Korea and Germany were low on publication efficiency (Fig. 2) There appears to be an inverse relationship between patents and papers for certain countries in a departure from Albuquerque's model (indicated by representative lines in Fig. 4). The countries on the line of lower slope have lower values of publications and patenting, and shown by Albuquerque to have lower values of GNP per capita, while those on the line with higher slope have higher values of publications and patenting and higher values of GNP per capita. The countries that stand away from the lines namely Japan, USA, Korea and Germany appear to be following a new trend. We conclude that certain countries that

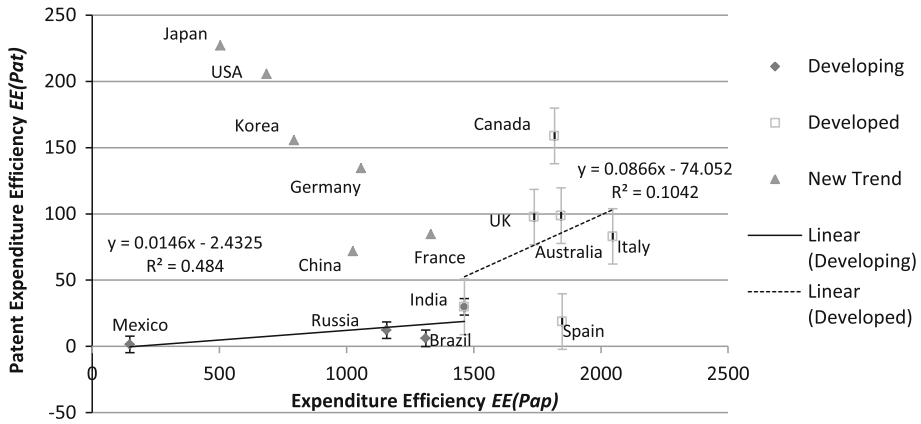


Fig. 4 Plot of patenting efficiency with respect to expenditure $EE(Pat)$ and paper efficiency with respect to expenditure $EE(Pap)$ showing the developing countries lying along the *lower line*, and the developed countries along the *line of higher slope*. Certain countries such as Japan, USA, Korea have now moved away from this distribution suggested by Albuquerque

have increased their GERD/GDP share, showing increased expenditures in R&D, show at the same time a lowered efficiency in the output of scientific papers. This appears to be compensated by high efficiency in the production of patents.

The funding for R&D or GERD is usually broken down into four sectors—the business sector, the government sector, the higher education sector and the non-profit sector. The contribution to R&D from the business sector refers to all R&D performed in the business sector regardless of the origin of the funding. R&D activities in the business sector are expected to be more closely related to the production of new products and processes, and therefore patenting. If we now look at the funding pattern of GERD from different sources for these countries, we find that 78.2 % of total R&D expenditure in Japan comes from the business sector. It is 67.3 % in the US, 67.6 % in Germany and only 45.1 % in the UK (2008 figures) (OECD 2011, Eurostat 2012) and 76.8 % for Korea (2005 figures) (Adams et al. 2013). In fact Japan and Korea are among the countries that have the highest percentage shares from the business sector (BERD) with the exception of a few countries like Israel, not included in our study. These input figures corroborate our analysis of output efficiency, indicating a shift from publications toward patenting in tandem with increased expenditure from the business sector in countries like Japan, USA, Korea and Germany. France and China also appear to be following this trend (Fig. 4).

Results

We began by exploring the question of efficiency of production of scientific papers and patents, for both developing and developed countries, with respect to inputs into the research system such as research expenditure and manpower. We followed a model by Albuquerque which suggested that for low levels of development countries are unable to translate their scientific knowledge into economic returns, where scientific publications are used as a proxy for knowledge and patents as an indicator of economic returns from R&D. Beyond a certain threshold in the efficient production of papers, developed countries become much more efficient in patent production. Using a modified definition of

efficiency, we find that around the period 2007–2008, several countries do not fall along the trend lines suggested by Albuquerque showing high efficiency in the production of patents together with reduced efficiency in paper production. We suggest that this is a novel trend among countries (USA, Japan, Korea, Germany and increasingly France and China) where a very high share of research expenditure in the business sector (BERD) is resulting in higher priority to patenting.

It was also noted that in terms of efficiency in the production of papers, Italy has the highest efficiency with respect to both expenditure and manpower. This is traced to low levels of funding in competing sectors which do not result in papers, together with highest growth rates of publication among European countries, as discussed below.

Discussion

It has been noted for some years now that the US share of scientific publications is declining. The link between declining shares of publications and relative components of research expenditure has been noted by Shelton (2008), Leydesdorff and Wagner (2009), Foland and Shelton (2010) and Shelton and Leydesdorff (2011), but their studies have been restricted to the highly developed countries. Our study includes a larger set of countries and at different stages of development. The efficiency indicators proposed by us show a low efficiency for publishing but a high efficiency in patenting for the USA, in comparison to other countries. This pattern is also followed by Japan, Germany and Korea. They deviate from the Albuquerque model where higher patenting was associated with higher publishing (above a certain publication threshold) and was supposed to be a discriminator for developed countries. France and China also appear to be following this trend. The reason for this is traced to higher investments from the business sector, and possibly greater deployment of manpower towards R&D leading to patenting rather than published papers. This adds another dimension that could not be accounted for in Albuquerque's model and is a novel finding of this paper.

Another question that arises is the reason for the very high efficiency of Italy with respect to other countries. The European countries have been studied in detail by Foland and Shelton (2010) and they show that Italy has the lowest expenditure on the military, which is a sector not associated with paper production. At the same time, its annual output of papers has been increasing more rapidly than other European countries like Germany, France, the UK, as well as the US and EU.

In summary, the efficiency indicators proposed here point towards the direction where greater emphasis is given—publications or patenting—in national priorities. They also identify countries that are more efficient and identify reasons for the same. The new trend appears to be a path of preferential patenting, fuelled by a greater share of funds from the business sector.

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