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Produce patents or journal articles? A cross-country comparison of R&D productivity change

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Abstract This paper compares R&D productivity change across countries considering the fact that national R&D expenditure may produce multiple outputs, including patents and journal articles. Based on the concept of directional distance function and Luenberger productivity index, this paper develops a Luenberger R&D productivity change (LRC) index and then decomposes it into R&D efficiency change (catch-up effect) and R&D technical change (innovation effect). Utilizing a panel dataset of 29 countries over the 1998–2005 period to implement the empirical estimation, the results show that the R&D productivity growth is mainly attributed to the innovation effect; meanwhile, non-OECD countries have better performance on both efficiency change and technical change than their OECD counterparts. Moreover, patent-oriented R&D productivity growth serves as the main source of national R&D productivity growth than the journal article-oriented one.

Keywords R&D productivity change · Patents · Journal articles

JEL Classification C67 · O33 · O57

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Introduction

The endogenous growth model claims that innovation is a main driver of sustainable long-run growth and this point has been widely supported in most empirical studies.[1] Thus, the efficiency and productivity of innovation process play a key role on fostering economic growth, inspiring many studies to assess whether R&D resources are used efficiently or not, e.g., Lee and Park (2005), Wang (2007), Wang and Huang (2007) and Cullmann et al. (2009). However, the widely examined R&D efficiency score in existing literature is a static measurement that it enables us to understand only the relative efficiency of transforming R&D inputs to outputs in the current period. It contains no information regarding driving forces of inter-temporal efficiency improvement, suggesting the dynamic measurement of R&D productivity change index is more informative to understand the dynamics of R&D activity, as it enables the policy makers to design appropriate R&D policies to efficiently foster innovations and promote technological progress.

Traditionally, the Malmquist productivity change index developed by Cave et al. (1982) is widely adopted to analyze the nature of efficiency change in various industries, such as manufacturing industry, banking and finance sector, and higher education sector.[2] For instance, Hashimoto and Haneda (2008) evaluate the change in R&D efficiency of Japanese pharmaceutical industry at both firm level and industry level. Their findings reveal that R&D efficiency of Japanese pharmaceutical industry has almost monotonically gotten worse throughout the study decade. Wu et al. (2006) examine the impact of intellectual capital on competitive advantage in Taiwanese IC design companies and find that approximately one-third of the sample companies had excellent efficiency in the intellectual capital management. Focusing on the same industry, Taiwan's IC design, Lu and Liu (2010) indicate that the R&D productivity growth is mainly attributed to the increase in technical change, and the efficiency gain found is largely the result of improvement in scale efficiency.

Despite there is a growing body of studies investigating R&D productivity change using firm-level data, studies using aggregate data remain very rare. Guan and Chen (2010) provide a framework of the non-radial input-oriented DEA-Malmquist approach to evaluate the R&D productivity change across Chinese provinces during 2000–2003 periods. Their findings show that seven provinces engage in R&D efficiently, but the overall performance of R&D productivity growth is relatively poor. As for the cross-country comparison of R&D productivity change, the only one, to our best knowledge, is Thomas et al. (2009) that uses the Malmquist productivity index to analyze R&D efficiency in 22 countries for the periods 2002–2004 and 2004–2006. In their empirical model, R&D expenditure and the number of full-time researchers are inputs, which produce two outputs, patents granted to residents and scientific publications. Their estimates show that all countries, except for the United Kingdom, experienced technical progress for the period of 2004–2006. Specifically, China exhibited a rapid increase in number of scientific publication and Korea showed the exemplary performance in patenting among residents in sampling periods, enabling these two countries to experience a higher productivity growth than other countries.

The rare studies suggest the need of more empirical studies. Crucially, some potential room for improvement remains. While the Malmquist productivity index is widely adopted to evaluate the R&D productivity change, Boussemart et al. (2003) indicate the Malmquist

[1] See Acemoglu et al. (2006) for a comprehensive survey of both theoretical and empirical literature on the innovation-economic growth nexus.

[2] Färe et al. (1994) take the Malmquist index of TFP growth and describe how decompose its index into various components.

productivity index may overestimate the productivity growth. Alternatively, the Luenberger productivity index can serve as the appropriate one on measuring R&D productivity growth (Boussemart et al. 2003; Managi 2003). Second, Malmquist productivity index is derived from the proportional distance function that assumes all factors have the same distance to the frontier, preventing us to examine the various contribution of each factor on productivity change. As various R&D outputs (e.g., patents and journal articles) have distinct production features, understanding the R&D productivity change contributed by each output factor is helpful for the policy authority to propose adequate R&D policy.

This paper aims to compare R&D productivity change across countries by providing the following distinct types of empirical evidence: First, although existing studies have measured R&D productivity change at the firm and industry level, few have investigated this issue using country level. This cross-country comparison study can provide insightful implications for R&D management and innovation policy. Second and most importantly, utilizing the concepts of directional distance function, this study develops the Luenberger R&D productivity change index (LRC). It enables us to adequately evaluate the R&D productivity change. This study further decomposed the LRC index into two components: one is the change in relative R&D efficiency, measuring a country is getting closer to or far away from its annual frontier (catch-up effect or fall-behind effect). The other is shift in the production frontier under the total-factor framework. The expanding technology frontier is generally contributed by innovations, technology upgrading, and diffusion, etc. This is the so-called the innovation effect. Third, existing studies evaluate only the overall productivity change index rather than the productivity change contributed by individual output. Assuming the distance to frontier varies across output factors, this study can precisely evaluate each factor's contribution (improvement or deterioration) to the overall productivity change.

Rest of this paper is organized as follows: Sect. 2 addresses the estimating methodology and describes the dataset. We follow the concept of Luenberger productivity index to construct the R&D productivity change and decompose it into efficiency change and technical change. The estimating results of various indexes of R&D productivity change are displayed and discussed in Sect. 3. Concluding remarks and policy implications are discussed in the final section.

Empirical methodology

This section introduces the construction of R&D productivity change index using Luenberger productivity index. To model the production process, we assume that F^t is the production technology that country k transforms multiple inputs, $x \in R_+^S$, into multiple outputs, $y \in R_+^M$, in time period t. F^t for each country is defined as the set of all feasible input–output vectors:

$$\mathrm{F}^t = \left\{ \left(x^k, y^k\right) : x \in R_+^S, y \in R_+^M, x \text{ can produce } y \right\} \quad (1)$$

The construction of the Luenberger productivity index relies on directional distance function, this study thus, following the Chambers et al. (1996), defines the directional distance function as:

$$\vec{D}_{(t)}(x^t, y^t;\ \mathrm{g}_x,\ \mathrm{g}_y) = \max\left\{ \beta \in \Re^+ \cap \{0\} : (x^t - \beta \mathrm{g}_x, y^t + \beta \mathrm{g}_y) \in \mathrm{F}^t \right\} \quad (2)$$

where $(\mathrm{g}_x,\ \mathrm{g}_y)$ is a nonzero vectors in $R_+^S \times R_+^M$. The directional technology distance function allows decision-making units (DMUs) to simultaneously seek the maximum expansion of outputs (y) and contraction of inputs (x) to optimize the production. The value of directional distance function equals to zero if a country is technically efficient, whereas the value of $\vec{D}_{(t)}(x^t, y^t;\ g_x,\ g_y) > 0$ indicates the production is inefficient. To measure productivity change, we have to evaluate the directional distance function in different time periods. The base period Luenberger R&D productivity change (LRC^t) index relative to the base period technology (F^t) is shown as:

$$LRC^t = \vec{D}_{(t)}(x^t, y^t;\ g) - \vec{D}_{(t)}(x^{t+1}, y^{t+1};\ g) \tag{3}$$

Similarly, the period $t + 1$ index relative to period $t + 1$ technology ($F^{t\ +\ 1}$) is displayed as:

$$LRC^{t+1} = \vec{D}_{(t+1)}(x^t, y^t;\ g) - \vec{D}_{(t+1)}(x^{t+1}, y^{t+1};\ g) \tag{4}$$

Therefore, we can establish the Luenbereger R&D productivity change index as follows:

$$LRC(x^t, y^t, x^{t+1}, y^{t+1}) = \frac{1}{2}\left[LRC^t + LRC^{t+1}\right] \tag{5}$$

If the value of index is less than, equal to, or larger than zero, it stands for productivity regress, no change, or progress between period t and $t + 1$, respectively.

Moreover, Chambers et al. (1996) indicate that Luenberger productivity index can be decomposed into efficiency change and technical change. Efficiency change equals the difference in the directional distance function between two periods, while technical change equals the average 'shift' in the frontier. Efficiency change measures changes in the position of production unit relative to the best-practice frontier over time and represents the so-called 'catching up' effect. That is, the convergence towards or divergence from the best practice. On the other hand, technical change equals the average 'shift' in the best-practice frontier from period to period and represents the 'innovation' effect, that is, the improvement or deterioration in the performance of best-practice production units. Following the decomposition of Chambers et al. (1996), this study further decomposes the LRC index into two parts, Luenberger R&D efficiency change (LREC) and Luenberger R&D technical change (LRTC), as follows:

$$\begin{aligned} LREC(x^t, y^t, x^{t+1}, y^{t+1}) &= \vec{D}_{(t)}(x^t, y^t;\ g) - \vec{D}_{(t+1)}(x^{t+1}, y^{t+1};\ g) \\ LRTC(x^t, y^t, x^{t+1}, y^{t+1}) &= \frac{1}{2}\Big[\vec{D}_{(t+1)}(x^{t+1}, y^{t+1};\ g) - \vec{D}_{(t)}(x^{t+1}, y^{t+1};\ g) \\ &\quad + \vec{D}_{(t+1)}(x^t, y^t;\ g) - \vec{D}_{(t)}(x^t, y^t;\ g)\Big] \end{aligned} \tag{6}$$

However, the commonly used Luenberger productivity index assumes a special case of proportional distance function that all factors have the same distance to the frontier. It prevents us to examine the possible difference in productivity change across output. Therefore, this study applies the technique of directional distance function to evaluate the value of distance function in Eqs. (5) and (6). As the goals of R&D activities focus on producing new and original innovations rather than saving R&D costs, we assume that the linear programming method of directional distance function aims to maximize the outputs (y) given the fixed inputs. Let there are S inputs and M outputs for each country in time t. The ith input and rth output variable of jth countries are represented by x^t_{ij} and y^t_{rj} in time t, respectively. Therefore, the directional distance functions for the DMU j in time t can be evaluated by the following linear programming (LP) model:

$$\begin{aligned} \vec{D}_t^k(x^t, y^t) &= \max_\beta (\beta_1 + \cdots + \beta_M)/M \\ \text{s.t.} \sum_{j=1}^{K} \lambda_j y_{rj}^t &\geq y_{rk}^t + \beta_r y_{rk}^t, r = 1, \ldots, M \\ \sum_{j=1}^{K} \lambda_j x_{ij}^t &\leq x_{ik}^t, \; i = 1, \ldots, S \\ \lambda_j \geq 0, \; \beta_r &\geq 0, j = 1, \ldots, K, \end{aligned} \tag{7}$$

where λ_j is the intensity variable that serves to form a convex combination of observed inputs and outputs. As shown in Eq. (7), the variable, β_r can be interpreted as the directional distance function of specific output. It is noteworthy that the true slacks, $\beta_r y_{rk}^t$, are based on the assumption of constant return to scale,[3] indicating the efficient level of outputs for achieving the overall technical efficiency. The calculation of $\vec{D}_{t+1}^k(x^{t+1}, y^{t+1})$ is similar to Eq. (6), where $t + 1$ is substituted for t. As for the evaluation of the two inter temporal directional distance functions, $\vec{D}_t^k(x^{t+1}, y^{t+1})$ and $\vec{D}_{t+1}^k(x^t, y^t)$, we can obtain the measures by solving the following linear programming problems:

$$\begin{aligned} \vec{D}_t^k(x^{t+1}, y^{t+1}) &= \max_\beta (\beta_1 + \cdots + \beta_M)/M \\ \text{s.t.} \sum_{j=1}^{K} \lambda_j y_{rj}^t &\geq y_{rk}^{t+1} + \beta_r y_{rk}^{t+1}, r = 1, \ldots, M \\ \sum_{j=1}^{K} \lambda_j x_{ij}^t &\leq x_{ik}^{t+1}, i = 1, \ldots, S \\ \lambda_j \geq 0, \beta_r &\geq 0, j = 1, \ldots, K \end{aligned} \quad \textit{and} \quad \begin{aligned} \vec{D}_{t+1}^k(x^t, y^t) &= \max_\beta (\beta_1 + \cdots + \beta_M)/M \\ \text{s.t.} \sum_{j=1}^{K} \lambda_j y_{rj}^{t+1} &\geq y_{rk}^t + \beta_r y_{rk}^t, r = 1, \ldots, M \\ \sum_{j=1}^{K} \lambda_j x_{ij}^{t+1} &\leq x_{ik}^t, i = 1, \ldots, S \\ \lambda_j \geq 0, \beta_r &\geq 0, j = 1, \ldots, K \end{aligned} \tag{8}$$

Finally, we can obtain the LRC, LREC as well as LRTC from solving the above linear programming problems.

Following the knowledge production function proposed by Pakes and Griliches (1984) and Griliches (1990), this paper sets up a framework of country-level knowledge production that multiple innovative inputs are invested to produce multiple innovative outputs. Referring to existing studies, we include R&D expenditure stock and full-time researchers and technicians as inputs.[4] Due to the unavailability of data on R&D expenditure stock, this study converts R&D expenditure flow into R&D expenditure stock using the perpetual inventory method.[5]

[3] As the scale of a country is hard to adjust in the short-run, most previous studies assumed an innovation production with constant returns to scale between inputs and outputs (e.g., Griffith et al. 2006; Hashimoto and Haneda 2008; Lee and Park 2005; Parisi et al. 2006).

[4] Total R&D expenditure is performed by both public and private sectors and covers the expenditure of basic research, applied research, and experimental development such as land, buildings, instruments and equipment, and other current cost on creative work undertaken systematically to increase the stock of knowledge.

[5] Following the assumptions widely adopted in previous studies (e.g., Hall and Mairesse 1995; Mairesse and Hall 1996), we assume a depreciation rate of 15 % for R&D expenditure stock. Moreover, as suggested in Guellec and van Pottelsberghe de la Potterie (2004), the growth rate is set to being an individual country's average annual rate of R&D growth.

Table 1 Summary statistics of output and input variables (1998–2005)

Name		Mean	SD	Minimum	Maximum
Output variables					
y_1	Patents[a]	13,756.9	39,830.5	3.6	240,902.8
y_2	Scientific journal articles[b]	18,648.1	36,539.9	133.0	205,320.0
Input variables					
x_1	Total R&D man power[a] (full-time equivalent units)	226,585.8	356,332.8	3,710.0	1,415,873.0
x_2	R&D capital stocks[c] (million US dollars in year 2000)	115,712.9	303,791.5	92.5	1,599,604.0

[a] Main Scientific Technology Indicators, OECD, Paris

[b] World Bank: World Development Indicators database

[c] R&D expenditure is collected from Main Scientific Technology Indicators, OECD, Paris, then transformed into R&D capital stock by using perpetual inventory method

As a country's innovative outputs are multidimensional, it may lead to only a partial view of national R&D productivity change if we consider only one output to compare R&D productivity change across countries. Thus, this study includes patents and scientific journal articles as innovative outputs. Patent is the most widely adopted measure of innovation outputs in existing innovation literature (Griliches 1990; Geisler 1995; Brown and Svensen 1998). However, the simple count of patent applications at home is likely biased due to the home advantage for patent applications and difference in patent quality across countries. Therefore, we adopt the number of patent applications in the European Patent Office (EPO) and the US Patent and Trademark Office (USPTO), because both indicators can be treated as 'new-to-the-world' innovations.[6] On the other hand, one country may produce other innovative outputs more efficiently due to its composition of national R&D. For instance, some R&D programs are essentially basic-research oriented and have the primary objective of publishing academic journal papers. Therefore, journal articles published in scientific and engineering fields are considered as another major output of research and they are widely used to evaluate the performance of researchers (OECD 2001). Indeed, this measure is also widely treated as another measure of national innovative output (Wang and Huang 2007). This study counts the number of articles published in journals of physics, biology, chemistry, mathematics, clinical medicine, biomedical research, engineering and technology, and earth and space sciences as one of the innovative outputs.

The dataset utilized in this study is a panel dataset of 29 countries, including 20 European countries, five Asian countries, and four North and South American countries during the 1998–2005 period.[7] The information regarding inputs are collected from the Main Scientific Technology Indicators (MSTI, OECD), whereas information concerning output variables are drawn from the database of the US Patent and Trademark Office (USPTO), MSTI, and World Development Indicators (WDI) (World Bank 2008). Since the

[6] For the pitfalls and advantages associated with equating patent counts with innovation, please see Furman et al. (2002) for a survey.

[7] The 29 countries include Belgium, the Czech Republic, Estonia, Finland, France, Germany, Hungary, Ireland, Italy, Latvia, Lithuania, the Netherlands, Poland, Portugal, Slovakia, Slovenia, Romania, Spain, the United Kingdom, China, Israel, Japan, South Korea, the Russian Federation, Singapore, Argentina, Mexico, Canada, and the United States.

Table 2 Correlation matrix of input and output variables

Variables	Correlation matrix			
Outputs				
Patents[a]	1.0000			
Scientific journal articles[b]	0.9634 (<0.001)	1.0000		
Inputs				
Total R&D man power[a] (full-time equivalent units)	0.7078 (<0.001)	0.7688 (<0.001)	1.0000	
R&D expenditure stocks[c] (million US dollars in year 2000)	0.9844 (<0.001)	0.9488 (<0.001)	0.7361 (<0.001)	1.0000

data covers a time span of 8 years, all variables in monetary units have been transformed into real variables in terms of million USD dollars in the year 2000. Table 1 describes the summary statistics of input and output variables.

Table 2 demonstrates the correlation matrix of input and output variables, whereby positive correlations exist between inputs and outputs, satisfying the isotonicity property that an output does not decrease with an increase in an input. The correlation coefficients between R&D stock and two outputs (patents and journal articles) are 0.9844 and 0.9488, respectively. A positive correlation coefficient of 0.7078 and 0.7668 is found between R&D manpower and two outputs, respectively. These results confirm isotonicity between any input and all of the two outputs in the linear programming model. This input–output framework can be applied to analyze the Luenberger R&D productivity change index in this study.

Empirical results

Estimation of Luenberger R&D productivity change

Table 3 displays the estimates of the Luenberger R&D productivity change (LRC) index for each country during the 1998–2005 period. Table 3 shows that the average LRC reached only a growth of 0.0992 % for the whole sample countries during the 1998–2005 period, on average. In terms of time trend, the estimated average R&D productivity change shows a positive growth, except for the period of 1999–2000. Specifically, 1998–1999 and 2002–2003 exhibited a significant higher productivity growth than other periods. From the perspective of degree of economic development, non-OECD countries experienced a higher Luenberger R&D productivity growth (0.127 %) than their OECD counterparts (0.0822 %). This finding is reasonable since non-OECD countries (normally developing countries) are devoting more and more R&D, attempting to promote their technological capability. From the regional perspective, European countries seem to have a higher R&D productivity growth than their Asian and American counterparts and this result is attributed to higher productivity growth experienced by non-OECD emerging European countries.

Which countries experienced better R&D performance in terms of productivity change? In fact, fifteen of 29 countries have enhanced their R&D productivity during the period, including Belgium, China, Czech Republic, Estonia, Hungary, Lithuania, Netherlands, Poland, Portugal, South Korea, Romania, Russian Federation, Slovakia Republic, Slovenia, and United States (see Appendix Table 7). Specifically, seven of these 15 countries

Table 3 Annual Luenberger R&D productivity change by regions (%)

Country	98/99	99/00	00/01	01/02	02/03	03/04	04/05	Average
All countries	0.2774	−0.1579	0.0535	0.0305	0.3767	0.0941	0.0201	0.0992
OECD	0.2344	−0.2228	0.1338	0.0781	0.1688	0.0768	0.1061	0.0822
Non-OECD	0.3478	−0.0517	−0.0779	−0.0474	0.7169	0.1223	−0.1208	0.1270
Europe	0.4067	−0.2440	0.0541	0.0713	0.4762	0.2157	0.0522	0.1474
Asia	0.2064	−0.1447	0.0952	0.0718	0.0768	0.1220	0.0892	0.0738
America	−0.2799	0.2559	−0.0016	−0.2250	0.2545	−0.5489	−0.2271	−0.1103

Table 4 Mean scores and ranking of LRC, PLRC, and JLRC by regions

Country	LRC (%)	PLRC (%)	JLRC (%)
All countries	0.0992	0.3670	−0.0766
OECD	0.0822	0.2750	−0.0250
Non-OECD	0.127	0.5176	−0.1610
Europe	0.1474	0.4616	−0.0777
Asia	0.0738	0.3721	−0.1055
America	−0.1103	−0.1122	−0.0351

performed a higher productivity growth than the average growth rate and most of them are developing or transitional economics, containing China, Lithuania, Romania, Slovakia Republic, and Slovenia. Despite developing or transitional countries may lack high-quality R&D personnel, advanced techniques of knowledge management, and other innovation complements, they generally strive to promote their technological capability through R&D and acquiring advanced knowledge from abroad, inducing them to have higher R&D productivity growth. As for OECD countries, Poland, a developing country, has the highest R&D productivity growth and Portugal is the second best performer among 29 countries. Poland stands out as a successful example of the transition from a central planned economy to a primarily market-based economy. Rapidly economic development, particular for upsurge in R&D and healthy higher education system, promote her technological capability to compete with other advanced OECD countries. On the other hand, establishing several science parks to help establishment of scientific, technological and knowledge-based businesses and providing financial and marketing and technological support to high-tech firms, Portugal strategies of developing high-tech industries enables this country to effectively promote its R&D productivity.

Since a country's R&D efforts can produce various innovative outputs, we are not only interested in the overall productivity change, but also productivity change in producing each output. Based on Eqs. (7) and (8), we calculate the patent-oriented Luenberger R&D productivity change (PLRC) index and journal-oriented Luenberger R&D productivity change (JLRC). Table 4 displays that the average scores of LRC, PLRC as well as JLRC.

Comparing the ranking of three indices, we find several interesting and important results. First, while the average LRC is positive as discussed previously, the average PLRC and JLRC is positive and negative during the sampling period, respectively. The statistics in lower panel of Table 4 shows that the patent-oriented Luenberger R&D productivity reached an average growth of 0.367 %, whilst the journal-oriented Luenberger R&D productivity experienced a decrease of 0.0766 %, on average. This finding implies that most countries may pay more attention to applying for patents rather than publishing journal papers. Another plausible reason is the increasingly competitive environment of international journals, preventing the sampling countries to publish journal articles proportional to their R&D input. Second, non-OECD countries perform better on patent-oriented Luenberger growth index, but they seem to encounter a more serious symptom of productivity decrease in journal-oriented Luenberger growth than OECD countries. From the regional perspective, Asian countries experienced the worst average JLRC among three regions and their positive LRC is mainly arising from the growth (0.372 %) of patent-oriented Luenberger productivity. American countries' performance is discouraged that all indices of productivity growth, including LRC, PLRC, and JLRC, are negative, on average.

It is also interesting to observe individual country's R&D productivity change that some countries exhibit consistent performance of various productivity growth indices, but some, and mostly transitional countries, experience divergent performance. As discussed above, Poland and Portugal have a higher overall R&D productivity growth among 29 countries. Indeed, their rapid productivity growth is driven by both patent-oriented and journal-oriented productivity growth. In terms of rankings on three productivity change index (see Appendix Table 8), Poland ranks first out of the 29 countries on the LRC and its relative performance on the PLRC and JLRC rank first and third, respectively. Portugal ranks second out of the 29 countries on LRC and its growth of PLRC and JLRC ranks forth and seventh, respectively. This result implies that the promotion of R&D productivity on publishing scientific journal articles plays also an important role in technical progress, because the scientific journal articles are essentially the innovation outputs of basic research as well as applied research. Therefore, the sustainable economic growth supported by innovations depends on creating the new applied-research oriented innovation such as patent, but also make more effort in researching the basic-research oriented innovation such as scientific journal articles.

On the other hand, some countries seem to lean on and specialize on specific innovation output as they undertake R&D activity. For instance, China ranks fourth out of the 29 countries on the LRC and this higher ranking is primarily attributed to its excellent performance of PLRC that ranks the top third. Alternatively, China's journal-oriented productivity growth ranked as the lowest among sample countries during the 1998–2005 period. Recently, the Chinese government has encouraged scholars to publish international journal articles aggressively using various incentive mechanisms. Lithuania and Latvia seem to have the similar situation that their rankings on patent-oriented productivity growth are high, but the corresponding rankings of journal-oriented productivity growth are quite low. These findings suggest that transitional countries' innovation activity seem to pay more attentions on applying for patents and it is partly because the patent-oriented productivity growth is more relevant to national R&D productivity growth.

However, Japan, Korea, and US show a conversely situation on the productivity growth of patents and journal articles. Overall, their rankings of journal-oriented productivity growth located on the first quartile, but their rankings of patent-oriented productivity growth are below 20. In fact, these countries devoted a higher ratio of R&D expenditure to GDP and were granted numerous patents from USPTO and EPO. From the perspective of static efficiency, their R&D efficiency in terms of patents is high (Wang 2007; Wang and Huang 2007) and the possible bottleneck they encounter is that the number of patent granted is not proportional to the increase in R&D expenditure.[8]

[8] One point worth noting is that the patent quality is not well considered in this paper.

Table 5 Annual Luenberger R&D efficiency change by regions (%)

Country	98/99	99/00	00/01	01/02	02/03	03/04	04/05	Average
All countries	−0.1290	0.1290	−0.0084	0.2667	0.0191	−0.0745	−0.2273	−0.0035
OECD	0.0406	−0.0406	0.1109	0.1629	−0.0972	−0.0672	−0.1111	−0.0003
Non-OECD	−0.4066	0.5643	−0.2176	0.7740	−0.2180	−0.1010	−0.3133	0.0117
Europe	−0.0728	0.0728	−0.0008	0.3239	0.0665	0.0680	−0.1873	0.0386
Asia	−0.0974	0.0974	−0.0060	0.3457	−0.0081	0.0346	−0.0239	0.0489
America	−0.4496	0.4496	−0.0496	−0.1177	−0.1839	−0.9236	−0.6817	−0.2795

In sum, a country's R&D activities can produce various innovative outputs, implying that its productivity growth performance of distinct output may vary significantly. Different with existing studies, our analysis help discover the difference in productivity growth of various innovative outputs across countries.

Components of Luenberger R&D productivity change

The productivity growth was considered to be the product of efficiency change and technical change. Using the formula of Eq. (6), this study decomposes the LRC into efficiency change and technological change and denotes these two components as LREC and LRTC, respectively. Tables 5 and 6 demonstrate the calculating results of Luenberger R&D efficiency change and technical change during the 1998–2005 period, respectively. We first look at the estimated Luenberger R&D efficiency change, as shown in Table 5.

Drawn from estimates in Table 5, it is surprisingly to see that the average LREC is negative, suggesting that the sample countries overall experienced a slightly decrease of 0.0035 % in R&D efficiency growth during 1998–2005. However, the average LREC shows a positive growth during periods 1999–2000 and 2001–2003, implying that the catch-up effect exists during these periods. Countries with different degree of economic development seem to have divergent performance of efficiency change. The average LREC of non-OECD countries is 0.0117, indicating that their R&D activities reach the catch-up effect of 0.0117 %, on average. Alternatively, the average LREC of OECD countries is negative, suffering a decrease of 0.0003 % on efficiency change. This finding suggests that during the catch-up process, R&D efficiency improvement serves as one of driving forces for developing countries and it is probably arising from the improvement of R&D resources for non-OECD countries, enabling them to innovate more efficiently. In terms of regional performance, Asian and European countries experienced the similar efficiency growth, whereas American countries suffered the deterioration of R&D efficiency.

Regarding individual country's performance on R&D efficiency change (see Appendix Table 9), the estimated LREC in three countries, Estonia, Hungary, and United States, are equal to zero in each period, showing a persistent same performance of R&D efficiency. Israel experienced also a persistently consistent R&D efficiency, except for 2000–2003. The time trend of efficiency of Spain and Korea show a converse situation that Korean R&D efficiency change was unchanged after 2002, whereas Spain experienced unchanged R&D efficiency changes and then suffered deterioration on R&D efficiency since 2003.

Overall, eight of 29 countries experienced improvement of R&D efficiency—that is, their R&D efficiency catches up to the production frontier. In specific, the R&D efficiency of China, Poland, Portugal, and Slovakia increases more than 0.2 % annually, particularly,

Table 6 Annual Luenberger R&D technical change by regions (%)

Country	98/99	99/00	00/01	01/02	02/03	03/04	04/05	Average
All countries	0.4064	−0.2869	0.0619	−0.2362	0.3576	0.1686	0.2474	0.1027
OECD	0.1938	−0.1822	0.0229	−0.0848	0.2661	0.1441	0.2173	0.0825
Non-OECD	0.7544	−0.4583	0.1257	−0.4840	0.5075	0.2087	0.2967	0.1358
Europe	0.4794	−0.3167	0.0549	−0.2526	0.4097	0.1477	0.2395	0.1088
Asia	0.3038	−0.2421	0.1012	−0.2739	0.0849	0.0874	0.1131	0.0249
America	0.1697	−0.1937	0.0480	−0.1074	0.4384	0.3746	0.4545	0.1692

Poland ranks the top in R&D efficiency improvement, reaching an average of 0.6012 %. There are also four countries, including Argentina, Mexico, Russian Federation, and Spain, confronting an efficiency decline with over 0.1 % annual change, especially for Argentina (−0.5544 %) and Mexico (−0.5388 %). The above analyses indicate that some countries try to catch up to the frontier, while the inequality of R&D efficiency exists around the world. The catch-up effect generally serves as one kind of driving forces to improving national R&D productivity. Therefore, how to improve national R&D efficiency is a topical issue for most countries.

The second component of Luenberger R&D productivity change is the LRTC, representing the shift in the technology of innovation production. As shown in Table 6, the average increase in LRTC is 0.1027 %, indicating that the technology of producing innovations progresses during the sampling period of 1998–2005. Combined with result of negative average LREC in Table 5, we can conclude that the positive R&D productivity change is mainly contributed by technical change rather than efficiency change. That is, the innovation effect dominates the catch-up effect. However, the average LRTC showed a decline in 1999–2000 and 2001–2002, particularly for 1999–2000. This is the reason why the overall R&D productivity declines while the R&D efficiency change is positive.

Similar to overall productivity change, non-OECD countries' performance of technical change is superior to that of OECD countries. On average, non-OECD countries experienced an annual growth of 0.1358 % on technical change that was higher than that of OECD countries, 0.0825 %. To compete with the OECD countries, non-OECD countries not only improve their resource allocation of R&D activities more efficiently, but also aggressively upgrade their technology ladder. Combined with the results in Tables 3, 5, and 6, one of the reasons why the average LRC of European is higher than Asian countries is that the 'innovation effect' serves as the main driving force of R&D productivity growth for European countries and they performs also similar 'catch-up effect' compared with Asian countries. Furthermore, even if American countries have a better performance of technical change than other two regions, the fall-behind effect in efficiency change is a main cause why their overall R&D productivity change is behind European and Asian countries.

Turing to examine individual country's performance of technical change (see Appendix Table 10), almost all countries have experienced a positive R&D technical change, on average, showing a shift in the technology frontier of producing innovations. Eleven of 15 countries were witnessed a higher technical progress than the average LRTC, especially for developing and transitional countries. Mexico, Portugal, Slovakia, Poland, and Romania rank as the top five countries in average growth rate of technical change. Alternatively, Korean performance of technical change was the worst during 1998–2005 that reached an annual decrease of 00375 %, on average. Over the past decade, developing or transitional countries have devoted more efforts to improve their technological capability through both internal and external sources, enabling them to experience a more rapid growth of promoting technology level. Furthermore, few countries such as Argentina, Mexico, and Spain perform an obvious technical progress than the average, but their performance of overall R&D productivity remains not well due to the fall-behind effect in efficiency change. Hence, when one country seeks to upgrade its technology level, it has to also use R&D resources more efficiently.

Concluding remarks and policy implications

The importance of innovation on sustainable economic growth has been widely recognized in both theoretical and empirical literature. To reach a stable and sustainable growth, most countries have aggressively devoted more efforts toward R&D activity. How to efficiently undertake R&D to promote R&D productivity is topical to most countries in the circumstance toward knowledge economy. This study applies the technique of directional distance function to develop a Luenberger productivity change index (*LRC*) and decomposes it into LREC and LRTC. Specifically, our approach can calculate the productivity change of each innovative outputs in the multiple outputs–multiple inputs production framework. Using a panel dataset of 29 countries over the 1998–2005 period to compare their R&D productivity change, the empirical estimates show that the R&D productivity growth is low, reaching only an average of 0.0992 % during the period 1998 to 2005. In terms of time trend, the estimated average R&D productivity change shows a positive growth during sampling periods, except for the period of 1999–2000. The average Luenberger R&D productivity growth of non-OECD countries is 0.127 %, which is higher than that of OECD countries, 0.0822 %. Moreover, this study finds that the higher R&D productivity growth is mainly attributed to the patent-oriented Luenberger R&D productivity growth, particularly for developing countries. Even though, sustainable development not only depends on creating the new applied-research oriented innovation such as patent, but also devoting efforts in basic-research oriented innovation, such as scientific journal articles.

The decomposition of R&D productivity growth shows that the Luenberger R&D efficiency change decreased slightly by 0.0035 %, on average. This fall-behind effect could be treated as one kind of penalties for deteriorating the national R&D productivity. Even though, the catch-up effect of efficiency change exists in non-OECD countries, suggesting that they improve their resource allocation of R&D activities more efficiently to catch up with the OECD countries. Alternatively, the average LRTC was 0.1027 % during the 1998–2005 period, suggesting that the overall R&D productivity growth is contributed mainly by technical change. Again, non-OECD countries experienced a higher growth of technical change compared with that of OECD countries.

The key policy implications inspired from this study is that, as R&D inputs can produce various innovative outputs and each country locates in different degree of economic development, the government should consider the question that how to allocate national R&D resources in various performers and what portfolio of innovative outputs are the best strategy for economic development.

Some important issues are worth further investigating. Due to the availability of R&D information for non-OECD countries, this study contains only eleven non-OECD countries. If R&D data for more non-OECD countries are available and contains a longer time period, it helps compare and clarify the difference in R&D productivity change between developing and developed countries. Moreover, if detailed data is available, examining individual sector's R&D productivity change can provide more insightful implications for R&D policy within a country.

Appendix

See Tables 7, 8, 9, and 10

Table 7 Annual Luenberger R&D productivity change by country (%)

Country	98/99	99/00	00/01	2-Jan	3-Feb	4-Mar	5-Apr	Average
Argentina	−0.7753	0.8495	−0.0522	0.1769	0.091	−1.1687	−1.0128	−0.2702
Belgium	0.0104	−0.1218	−0.0847	0.1397	0.0757	0.0378	0.0662	0.0176
Canada	0.0232	−0.179	−0.1127	0.0114	0.0317	0.0511	0.0613	−0.0161
China	0.6884	0.2738	0.3693	0.0825	0.2433	0.4279	0.4819	0.3667
Czech	−0.2076	0.3412	0.4059	0.4458	−0.2409	0.2308	−0.5412	0.062
Estonia	0.2663	−0.2322	0.1766	−0.4112	0.2728	−0.0243	0.1845	0.0332
Finland	0.0273	−0.2074	0.1044	−0.08	−0.0665	0.004	−0.0503	−0.0383
France	0.0529	−0.1796	−0.0522	−0.0367	0.0226	−0.0082	0.0114	−0.0271
Germany	−0.0578	−0.0138	0.0175	−0.0163	−0.1253	0.0404	0.0272	−0.0183
Hungary	0.2614	−0.1311	−0.1144	−0.071	0.0791	0.0813	−0.0327	0.0104
Ireland	0.05	−0.2078	0.002	−0.0015	−0.1785	0.1026	0.1362	−0.0138
Israel	−0.0676	−0.0573	−0.0051	0.0141	0.0391	0.0174	0.0395	−0.0028
Italy	0.1553	−0.3125	0.0416	−0.1397	0.1761	0.0882	−0.087	−0.0112
Japan	0.1018	−0.1997	0.0208	0.016	−0.0078	0.0046	−0.0445	−0.0155
Latvia	−0.9481	1.1283	−0.0466	−0.064	−0.0419	0.2918	−0.6951	−0.0536
Lithuania	1.8766	−1.2744	−0.1147	−3.166	5.9673	−0.0492	−1.7478	0.2131
Mexico	−0.362	0.3343	0.155	−1.1003	0.9011	−1.0807	−0.0067	−0.1656
Netherlands	0.0342	−0.1319	0.0458	0.0084	−0.0127	0.0472	0.0417	0.0047
Poland	2.4023	−1.2851	1.5846	2.1389	0.9948	0.74	0.0537	0.947
Portugal	1.4896	−1.2691	0.3506	0.11	1.7263	0.6393	2.2709	0.7597
R Korea	0.0892	−0.375	0.0058	0.2817	0.0923	0.0514	0.0241	0.0242
Romania	1.0115	−0.175	0.3797	−0.5384	1.0522	0.9043	−0.1634	0.353
Russia	0.0701	0.1048	−0.2797	−0.4724	−0.2373	0.3311	0.6135	0.0186
Singapore	0.22	−0.3654	0.0851	−0.0352	0.0168	0.1087	−0.0551	−0.0036
Slovakia	1.9445	−1.3184	−0.986	3.209	0.048	0.3075	1.2211	0.6322
Slovenia	−0.46	0.4973	−0.3839	0.6829	0.4342	0.1986	−0.1953	0.1105
Spain	0.1563	−0.0938	0.0324	−0.1087	−0.3967	0.2645	−0.0755	−0.0316
UK	−0.0013	0.0028	0.0023	−0.203	−0.0262	0.0858	0.0062	−0.0191
USA	−0.0056	0.0187	0.0036	0.0118	−0.006	0.0026	0.0498	0.0107

Table 8 Mean scores and ranking of LRC, PLRC, and JLRC in each country

Country	LRC (%)	Ranking	PLRC (%)	Ranking	JLRC (%)	Ranking
Argentina	−0.2702	29	−0.4057	29	−0.028	14
Belgium	0.0176	12	0.0619	18	−0.0166	9
Canada	−0.0161	21	0.0555	19	−0.0537	21
China	0.3667	4	1.6314	3	−0.6647	29
Czech	0.062	8	0.0836	16	−0.0516	20
Estonia	0.0332	9	0.1335	9	−0.0671	23
Finland	−0.0383	26	0.0625	17	−0.093	24
France	−0.0271	24	0.0233	25	−0.0333	15
Germany	−0.0183	22	0.0108	26	−0.0474	18
Hungary	0.0104	14	0.0846	15	−0.0639	22
Ireland	−0.0138	19	0.0854	14	−0.0263	13
Israel	−0.0028	16	0.0361	22	−0.0417	16
Italy	−0.0112	18	0.0948	13	−0.0209	10
Japan	−0.0155	20	0.0455	21	0.0141	5
Latvia	−0.0536	27	0.3037	7	−0.5002	28
Lithuania	0.2131	6	0.8229	6	−0.3418	27
Mexico	−0.1656	28	−0.1294	28	−0.0495	19
Netherlands	0.0047	15	0.0996	11	−0.0261	12
Poland	0.947	1	2.6431	1	0.0291	3
Portugal	0.7597	2	1.6139	4	0.0047	7
R Korea	0.0242	10	0.0322	23	0.1471	1
Romania	0.353	5	1.0135	5	0.0079	6
Russia	0.0186	11	0.0949	12	−0.1719	26
Singapore	−0.0036	17	0.1156	10	0.0177	4
Slovakia	0.6322	3	1.7119	2	−0.0248	11
Slovenia	0.1105	7	0.2356	8	0.0433	2
Spain	−0.0316	25	0.0469	20	−0.1101	25
UK	−0.0191	23	0.0052	27	−0.0433	17
USA	0.0107	13	0.0307	24	−0.0093	8

Table 9 Annual Luenberger R&D efficiency change by country (%)

Country	98/99	99/00	00/01	2-Jan	3-Feb	4-Mar	5-Apr	Average
Argentina	−1.22	1.22	−0.1145	0.4423	−0.6567	−1.7631	−1.7889	−0.5544
Belgium	0.0795	−0.0795	−0.1314	0.1347	0.0582	−0.012	−0.0172	0.0046
Canada	0.1193	−0.1193	−0.1497	0.0102	0.0144	−0.0365	−0.0115	−0.0247
China	−1.2274	1.2274	−0.064	1.3156	−0.0575	0.1682	0.1553	0.2168
Czech	−0.6313	0.6313	0.4196	1.1272	−1.068	0.1334	−1.0594	−0.0639
Estonia	0	0	0	0	0	0	0	0
Finland	0.117	−0.117	0.1489	−0.1026	−0.1306	−0.0104	−0.1193	−0.0306
France	0.1326	−0.1326	−0.1049	−0.0475	0.0042	−0.0499	−0.1103	−0.0441
Germany	0	0	0	−0.0519	−0.2348	0.0232	−0.0208	−0.0406

Table 9 continued

Country	98/99	99/00	00/01	2-Jan	3-Feb	4-Mar	5-Apr	Average
Hungary	0	0	0	0	0	0	0	0
Ireland	0.1119	−0.1119	−0.0144	−0.0005	−0.2017	−0.0136	0.0309	−0.0285
Israel	0	0	−0.0352	0.0091	0.0261	0	0	0
Italy	0.2442	−0.2442	0.0838	−0.2532	0.2532	0	−0.2496	−0.0237
Japan	0.201	−0.201	0.0242	−0.0194	−0.003	−0.0082	−0.1187	−0.0179
Latvia	−1.391	1.391	−0.2116	0.5071	−0.2243	0.3599	−0.6865	−0.0365
Lithuania	0.6069	−0.6069	−0.2825	−2.1634	4.2651	−0.0409	−1.7726	0.0008
Mexico	−0.6977	0.6977	0.0659	−0.9231	−0.0933	−1.8946	−0.9262	−0.5388
Netherlands	0.102	−0.102	0	0	0	0	0	0
Poland	−0.049	0.049	1.5564	2.5154	0.1939	0.2398	−0.297	0.6012
Portugal	0.7463	−0.7463	0.1223	0.4393	0.4998	0.4344	1.2901	0.398
R Korea	0.2555	−0.2555	−0.025	0.4574	0	0	0	0.0618
Romania	−0.788	0.788	0.2885	0.1976	0.0635	0.4281	−0.5938	0.0548
Russia	−0.4777	0.4777	−0.4645	0.2606	−0.7659	−0.0037	0.2028	−0.1101
Singapore	0.2837	−0.2837	0.07	−0.0342	−0.0063	0.0131	−0.1562	−0.0162
Slovakia	0.4477	−0.4477	−1.05	3.4913	−0.7925	−0.1119	0.4586	0.2851
Slovenia	−0.7064	0.7064	−0.3766	0.7766	0.4518	0	−0.4109	0.063
Spain	0	0	0	0	−1.0051	−0.0063	−0.2926	−0.1863
UK	0	0	0	−0.3535	−0.0375	−0.0097	−0.0988	−0.0714
USA	0	0	0	0	0	0	0	0

Table 10 Annual Luenberger R&D technical change by country (%)

Country	98/99	99/00	00/01	2-Jan	3-Feb	4-Mar	5-Apr	Average
Argentina	0.4447	−0.3704	0.0623	−0.2653	0.7478	0.5944	0.7761	0.2842
Belgium	−0.0691	−0.0423	0.0467	0.005	0.0174	0.0498	0.0834	0.013
Canada	−0.0961	−0.0597	0.037	0.0012	0.0173	0.0876	0.0728	0.0086
China	1.9157	−0.9535	0.4334	−1.2331	0.3008	0.2596	0.3266	0.1499
Czech	0.4237	−0.2901	−0.0137	−0.6814	0.8271	0.0974	0.5182	0.1259
Estonia	0.2663	−0.2322	0.1766	−0.4112	0.2728	−0.0243	0.1845	0.0332
Finland	−0.0897	−0.0904	−0.0445	0.0227	0.0641	0.0143	0.069	−0.0078
France	−0.0798	−0.0469	0.0527	0.0108	0.0184	0.0417	0.1217	0.017
Germany	−0.0578	−0.0138	0.0175	0.0357	0.1095	0.0173	0.048	0.0223
Hungary	0.2614	−0.1311	−0.1144	−0.071	0.0791	0.0813	−0.0327	0.0104
Ireland	−0.0619	−0.0959	0.0164	−0.001	0.0232	0.1163	0.1053	0.0146
Israel	−0.0676	−0.0573	0.0301	0.005	0.013	0.0174	0.0395	−0.0028
Italy	−0.0889	−0.0684	−0.0422	0.1135	−0.0771	0.0882	0.1626	0.0125
Japan	−0.0992	0.0013	−0.0034	0.0354	−0.0049	0.0129	0.0742	0.0023
Latvia	0.443	−0.2627	0.1651	−0.571	0.1824	−0.0681	−0.0086	−0.0171
Lithuania	1.2697	−0.6675	0.1678	−1.0027	1.7022	−0.0083	0.0248	0.2123
Mexico	0.3357	−0.3634	0.0891	−0.1772	0.9944	0.8139	0.9195	0.3731
Netherlands	−0.0677	−0.0299	0.0458	0.0084	−0.0127	0.0472	0.0417	0.0047

Table 10 continued

Country	98/99	99/00	00/01	2-Jan	3-Feb	4-Mar	5-Apr	Average
Poland	2.4513	−1.3342	0.0282	−0.3764	0.8009	0.5002	0.3508	0.3458
Portugal	0.7432	−0.5227	0.2284	−0.3293	1.2265	0.2049	0.9808	0.3617
R. Korea	−0.1663	−0.1194	0.0308	−0.1757	0.0923	0.0514	0.0241	−0.0375
Romania	1.7994	−0.963	0.0913	−0.736	0.9887	0.4762	0.4304	0.2982
Russia	0.5477	−0.3728	0.1848	−0.7331	0.5286	0.3348	0.4107	0.1287
Singapore	−0.0637	−0.0817	0.0151	−0.001	0.0231	0.0957	0.1011	0.0127
Slovakia	1.4967	−0.8707	0.064	−0.2823	0.8405	0.4194	0.7625	0.3472
Slovenia	0.2464	−0.2091	−0.0072	−0.0937	−0.0176	0.1986	0.2156	0.0475
Spain	0.1563	−0.0938	0.0324	−0.1087	0.6084	0.2709	0.2171	0.1547
UK	−0.0013	0.0028	0.0023	0.1506	0.0113	0.0955	0.105	0.0523
USA	−0.0056	0.0187	0.0036	0.0118	−0.006	0.0026	0.0498	0.0107

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