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Total Factor Productivity and R&D Capital in Manufacturing Industries

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ABSTRACT

This study analyzes total factor productivity in manufacturing industries for a sample of OECD countries. The estimates of Malmquist indexes clearly indicate that research and development (R&D) capital is an important determinant of productivity growth in manufacturing industries. The empirical results also show that it is the pace, not the intensity, of R&D investment that is significantly related to the extent to which R&D capital formation contributes to output growth. Furthermore, this study finds that productivity gains in manufacturing industries depend importantly on R&D spillovers as well.

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I. Introduction

Which output growth is actually due to improvement in the way a given level of inputs are utilized and how much should be simply assigned to input accumulation? This dichotomy between productivity and input accumulation has been a hotly debated subject of growth analysis, and been analyzed mainly in the context of total factor productivity (TFP). In estimating TFP growth, aggregate input proxies typically include two types of inputs, labor and fixed capital. However, it is increasingly recognized that knowledge capital is an equally, if not more, important input in fostering output growth.

In fact, manufacturing firms in industrial countries tend to spend sizeable sums on their R&D activities. For a sample of 14 OECD countries, R&D expenditures in manufacturing are found to be, on average, about five percent of the total value added and 35 percent of physical capital investment over the period of 1982-1993 (Table 1). In particular, firms in the fabricated metal products industry spent on their R&D, on average, about 70 percent as much as they did on investment in fixed capital over the period.[1] All these indicate that R&D is a quite costly factor of production in manufacturing. However, many studies have also found the rate of return on R&D is much higher than that on investment in fixed capital, suggesting potentially significant contributions of R&D to output growth (see Griliches (1994) for a review).

In this paper, we try to incorporate R&D expenditures explicitly into the analysis of TFP growth for a sample of OECD countries. For this purpose, we apply the Malmquist TFP index approach. The Malmquist index, in theory, is shown to be equivalent to the Törnqvist index from the growth accounting framework under certain conditions including the translog technology. For actual estimation of indexes, however, each approach has its own merits and limitations. With regard to inclusion of R&D capital as an additional input in measuring TFP growth, the growth accounting framework has clear limitations. For one, there is no ready estimate of the corresponding share-weight for R&D capital. In contrast, Malmquist indexes have been used mainly in the context of non-parametric frontier analysis, and subsequently not subject to share-weight restrictions.

A number of studies compare relative productivity growth of different countries using the Malmquist index, but very few incorporate R&D expenditures explicitly into their analysis.[2] By considering R&D capital one of input variables, our findings show the relative performance of a sample of OECD countries in productivity growth when their spending on R&D is also taken into account. Furthermore, the comparison of TFP indexes between with and without R&D capital input sheds light on the extent to which R&D capital formation contributes to output growth. We find the relative contribution of R&D capital formation to output growth

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[1] The industry includes metal products, non-electrical and electrical machinery, office and computing machinery, shipbuilding, motor vehicles, aircraft, and other transport equipment industries.

[2] Typically, only labor and fixed capital are considered input variables. See, for example, Färe et al. (1994), Taskin and Zaim (1997), Arcelus and Arozena (1999), and Maudos et al. (2000). One notable exception is Maudos et al. (1999) which include human capital as an additional input besides labor and fixed capital in calculating the Malmquist index.

depends more on the pace than on the intensity of R&D investment.

This paper is organized as follows. Section II outlines the Malmquist TFP index and its decomposition. This is followed by a description of data used in this paper. Section IV contains a discussion of estimation results. Conclusions are made in the last section.

II. The Malmquist Total Factor Productivity Index

To estimate productivity growth rates, we use the Malmquist approach proposed by Caves et al. (1982). The basic idea of this method is to construct the best-practice frontier using data on input-output combinations of a sample of countries (or industries or firms), and measure the distance between any particular observation and the frontier. Following Shephard (1970) and Caves et al. (1982), the output distance function at time t, D_o^t, is defined as follows:

$$D_o^t(x^t, y^t) = \inf\{\theta : (x^t, y^t/\theta) \in S^t\} \quad (1)$$

where S^t denotes the production technology which is defined as S^t = { (x^t, y^t) : x^t can produce y^t at time t }. x^t and y^t are vectors of inputs and outputs at time t respectively. Note that $D_o^t \leq 1$ corresponds to $(x^t, y^t) \in S^t$, and that $D_o^t = 1$ indicates that (x^t, y^t) lies on the technology frontier or boundary. Caves et al. (1982) define the output-based Malmquist index between periods t and t+1 as

$$M_o(x^{t+1}, y^{t+1}, x^t, y^t) = \left[\frac{D_o^t(x^{t+1}, y^{t+1})}{D_o^t(x^t, y^t)} \frac{D_o^{t+1}(x^{t+1}, y^{t+1})}{D_o^{t+1}(x^t, y^t)}\right]^{1/2} \quad (2)$$

A value of M_0 greater than unity indicates positive growth of TFP from period t to t+1, and a value less than unity represents deterioration in TFP.[3] This index is more useful for comparing the relative productivity growth of different countries, industries or firms than the TFP residual from the growth accounting framework. In terms of the TFP residual, for example, a country can show a much more rapid productivity growth than other countries simply because it starts from a lower level.[4]

The growth accounting method such as the Törnqvist index implicitly assumes that all units of production are technically efficient. If this assumption does not hold, the estimated productivity change will fail to represent the true technological progress. In contrast, the Malmquist index allows technical inefficiency by relying on the technology frontier concept. Following Färe et al. (1994), the Malmquist index in Equation (2) can be rewritten as

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[3] If the technology exhibits constant returns to scale, the output-based and input-based Malmquist indexes will provide the same measure of productivity change.

[4] This possibility is discussed in the huge literature on convergence theory. See Baumol (1986), Abramovitz (1990) and Dowrick and Nguyen (1989) among others.

$$M_o(x^{t+1}, y^{t+1}, x^t, y^t) = \frac{D_o^{t+1}(x^{t+1}, y^{t+1})}{D_o^t(x^t, y^t)} \times \left[\frac{D_o^t(x^{t+1}, y^{t+1})}{D_o^{t+1}(x^{t+1}, y^{t+1})} \frac{D_o^t(x^t, y^t)}{D_o^{t+1}(x^t, y^t)} \right]^{1/2} \qquad (3)$$

Equation (3) shows the decomposition of the Malmquist index into two basic components - efficiency change (EC) and technical change (TC).[5] The first ratio on the right hand side of Eq. (3) represents the change in technical efficiency or catch-up effect between the two periods *t* and *t*+1 (EC), and the term inside the bracket shows the change in technology (TC). If a sufficient number of observations are provided in each period, these change indexes based on pairs of successive periods can then be calculated.

For estimation of technology frontiers, several methods have been developed since Farrell (1957). In this study, we use the data envelopment analysis (DEA) approach to estimate the frontiers and calculate Malmquist indexes. In the DEA approach, the best-practice frontiers are estimated by non-parametric linear programming methods. In solving optimization problems, the DEA focuses on all individual observations whereas other statistical approaches usually concern average values.

III. Data

Our sample consists of 14 OECD countries for which data on fixed capital investment and R&D investment are available over the period of 1982-1993: Canada, Denmark, Finland, France, Germany, Italy, Japan, Korea, the Netherlands, Norway, Spain, Sweden, the United Kingdom, and the United States.[6] For these countries, we calculate Malmquist indexes and their components for the whole manufacturing sector as well as individual industries at the two digit ISIC level using data from the OECD STAN and ANBERD. We also use data from the Science and Technology Annual (STA) for R&D expenditures figures of Korea.[7] The period 1982-1993 is chosen due to data unavailability at the two digit ISIC level in Korea before 1982, and also because of data inconsistency in Germany after 1993 stemming from its unification.

Our measure of aggregate output is value-added in manufacturing; labor, fixed capital stock and R&D capital stock are our aggregate input proxies. Labor is defined as the number of workers, and fixed capital stock is calculated from gross fixed capital formation using the perpetual inventory method with the depreciation rate of 15 percent as in Verspagen (1997). R&D capital stock is calculated from R&D expenditures in ANBERD and STA using the depreciation rate of 15 percent as in capital stock. These variables are converted to U.S. dollars using the purchasing power parity (PPP) exchange rate from the STAN database.

IV. Estimation Results

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5 Efficiency change can be further divided into scale change and pure efficiency change when the variable returns to scale (VRS) technology is assumed (Färe et al., 1994).

6 Strictly speaking, Korea was not an OECD member country during the period this study covers. Korea joined the OECD in 1996.

7 The STA was published by the Ministry of Science and Technology of Korea.

Productivity Growth, Technical Change and Efficiency Change

We assume constant returns to scale (CRS) as underlying technology and calculate productivity growth using DEA approach.[8] We first calculate the Malmquist index and its components with only two types of inputs that are traditionally considered – labor and fixed capital stock – and then repeat the same exercise with the stock of R&D capital included as an additional input variable.[9] The results shown in Table 2 indicate robust productivity growth in manufacturing for our sample of OECD countries over the period 1982-1993. During the period, TFP in the manufacturing sector as a whole is found to increase, on average, by 4.0 percent per annum with labor and fixed capital stock considered only input variables, and by 3.6 percent per annum when R&D capital stock is considered an additional input variable. The decomposition of the Malmquist indexes shows that majority of such productivity growth came from innovation (TC) rather than improvements in efficiency (EC). This tends to be in line with the findings of most previous studies on a group of OECD countries.[10]

Table 2 shows that individual industries also exhibit similar patterns, but with great variation among themselves in the extent of productivity growth. During our study period, the chemical products industry in particular stands out in terms of technological progress.[11] Not only did the industry register highest TFP growth during the period, but also its high productivity growth was mainly due to innovation rather than efficiency catch-up. In fact, the industry, on average, showed regress in its catch-up performance during the period. The wood products and furniture industry is another industry whose TFP growth is found to have been mainly driven by innovation with the average values of EC less than unity.

By explicitly integrating R&D capital into the analysis of productivity growth, our findings throw light on the extent to which R&D capital formation contributes to output growth. Table 2 clearly indicates that some of output growth in manufacturing, which is ascribed to "costless" productivity growth when only labor and fixed capital are considered input variables, is, in fact, due to "costly" R&D capital formation. In addition, it is found to be technological progress rather than improvements in efficiency that is driven by the accumulation of R&D capital. The rate of efficiency change actually increases on average, albeit by a small margin of 0.1 percent, with the introduction of R&D capital as an additional input.

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[8] Variable returns to scale (VRS) may be an alternative technology, but the Malmquist index is equivalent to the traditional notion of total factor productivity under a CRS benchmark (Färe et al., 1997; Ray and Desli, 1997). For calculation of indexes, we use DEAP version 2.1 (Coelli, 1996).

[9] The significance of R&D capital as an additional input in the DEA model was tested using the Banker test (Banker, 1996). The test results suggest that the inclusion of R&D capital is statistically significant.

[10] For example, Perelman (1995) finds that, for eleven OECD countries, the TFP growth in manufacturing was 1.6 percent, the technological progress 1.8 percent and the efficiency change -0.14 percent over the period of 1970-1987.

[11] The industry includes chemicals, drugs and medicines, petroleum refineries and products, and rubber and plastic products industries.

According to our findings, the effect of R&D capital formation on innovation is most pronounced in the wood products and furniture industry. In this industry, the average value of the Malmquist index falls by 2.1 percent with the average value of TC going down from 4.0 percent to 1.7 percent when R&D capital input is included. The textiles industry and the basic metal industry follow behind, but to a much lesser degree, with their average values of TC reduced by 1.3 percent and 1.2 percent, respectively, after the introduction of R&D capital input. The output growth in the chemical products industry is also found to depend on R&D capital formation substantially. The introduction of R&D capital input reduces the average value of the industry's Malmquist index by 1.5 percent. Unlike other industries, however, the reduction is split relatively evenly between innovation and efficiency improvement. The accumulation of R&D capital is found to significantly arrest the deterioration in the industry's efficiency catch-up.

Table 3 provides a summary description of the average performance of each country in TFP growth as well as the technical-change and efficiency-change over the period 1982-1993. The relative standing of our sample countries in TFP growth tends to remain stable regardless of whether R&D capital is included as an additional input or not. The rank correlation between with and without R&D capital input is, on average, more than 80 percent over the period. In line with previous findings, the United States is consistently technically efficient in manufacturing, and its productivity growth is entirely driven by technological progress. These results for the United States hold true regardless of whether R&D capital input is included or not.

Japan is another country whose productivity growth is analyzed frequently in empirical literature. One of the issues attracting most attention in the context of Japan is which factor -- technical change or efficiency change -- is a major force behind productivity growth in Japan. The existing evidence is not conclusive. For example, Perelman (1995) finds that Japan's productivity growth in manufacturing is driven mainly by efficiency catch-up when it is estimated using the non-parametric approach. The parametric approach assigns a more dominant role to technical change, but efficiency change still accounts for more than forty percent of the country's productivity growth. Färe et al. (1994) also present similar results based on aggregate GDP data of a sample of OECD countries, suggesting the importance of efficiency catch-up process in Japan's productivity growth. In contrast, Maudos et al. (2000) report that efficiency change in Japan tends to become pale in comparison to technical change, using aggregate GDP data. Our results based on manufacturing data support the significance of technological progress as a main source of productivity growth in Japan. We find that Japan's TFP growth in manufacturing is mostly attributable to technical change rather than efficiency change. On average, Japan exhibits actual deterioration in its technical efficiency over the study period regardless of whether R&D capital is included as an additional input or not.

Of the countries in our sample, we note that Korea incurs the biggest fall in TFP growth when R&D capital is included as an additional input. Korea has the highest TFP growth in the sample at 7.5 percent per year on average when labor and fixed capital are only inputs. Once R&D capital input is included, however, it becomes a country with the slowest growth at 0.6 percent per year, only next to Spain which experiences actual productivity regress most of time during the period this study covers. In other words, most of relatively high productivity growth in the Korean manufacturing sector disappears once R&D capital formation is taken into account. This strongly suggests that manufacturing output growth in Korea depended critically on R&D capital formation over the period of 1982-1993. It also appears that R&D capital formation played a key role not only in facilitating technological progress in the country's manufacturing sector, but also in expediting the sector's catch-up with the OECD best-practice over the period.

R&D Intensity and Growth: Effects on R&D Contributions to Output Changes

Given the apparent impact of R&D capital formation on output growth, we may ask output growth of which country depends more on R&D capital formation. Is it a country investing in R&D more intensively? Or is it a country accelerating its R&D investment more agressively? In Korea where R&D capital formation appears to play a key role in manufacturing output growth, for example, R&D investment grew most rapidly among our sample firms -- at more than 20 percent per year on average over the period 1982-1993. In contrast, Korea does not stand out as much in its intensity of R&D investment. Korea's expenditures on R&D as measured by a share of the total value added in manufacturing, standing at about four percent per year on average over the period, are below the sample countries average of more than five percent per year. In the six of eight industries, Korea's intensity in R&D investment is lagging behind the sample countries average.

To find any systematic evidence on this, we take differences in rates of TFP growth as well as technical change and efficiency change by subtracting the rate under the two input case from the one under the three input case, and then regress these differences on each of the two variables: R&D expenditures as a share of the industry's total value added and rates of growth in R&D expenditures. We control for the country-specific effects omitted from the regressions by using fixed effects approach in the panel data analysis.

The results summarized in Table 4 indicate that it is the pace, not the intensity, of R&D investment that determines the extent to which R&D capital formation contributes to output growth. That is, the growth rates of R&D expenditures tend to be significantly related to differences in rates of TFP growth whereas R&D expenditures as a share of total value added are found to be non-significant most of time. The accelerating pace of R&D investment in manufacturing appears to enhance the contribution of R&D capital formation to output growth both by facilitating technological progress and by expediting catch-up with the industry's best-practice. The growth rate of R&D expenditures is significantly related to not only differences in rates of TFP growth but technical change and efficiency change as well. At the industry level, the accelerating pace of R&D investment also tends to enhance the contribution of R&D capital formation to output growth in a statistically significant way in most industries. However, this relationship is much less pronounced and often non-significant for technical change and efficiency change.

R&D Spillovers: Effects on Productivity Growth

Our empirical results clearly indicate that cumulative R&D is an important determinant of productivity growth in manufacturing. However, industries in our sample of OECD countries still exhibit substantial productivity growth even after the effect of their own R&D capital formation is taken into account. Such productivity growth may result from various factors like organizational and structural reform, or more importantly the innovation from sources other than industries' own cumulative R&D activities. There exists, in fact, convincing empirical evidence that the gap between social and private rates of return from industrial innovations is indeed huge, suggesting a significant role of inter-firm or inter-industry diffusion of innovations for productivity growth.[12] Furthermore, the diffusion of innovation is not confined to within the national border. Coe and Helpman (1995) provide strong empirical evidence that a country's productivity growth depends not only on its own R&D capital stock, but also on the R&D capital stocks of its trade partners.

In determining the effect of R&D spillovers on productivity, we consider two types of spillovers: domestic R&D spillovers across industries and international spillovers within a single industry. Our simplest equation has the following specification for industry *j*:

$$M_{i,t+1}^{j} = \alpha_0^j + \alpha_R^j \frac{R_{i,t+1}^j - R_{i,t}^j}{R_{i,t}^j} + \alpha_F^j \frac{F_{i,t+1}^j - F_{i,t}^j}{F_{i,t}^j} \qquad (4)$$

where *i* is a country index, $M_{i,t+1}^{j}$ is the Malmquist index between years *t* and *t*+1 with R&D capital stock included as an additional input variable, R^j represents the sum of domestic R&D capital stocks in industries other than industry *j*, and F^j represents the foreign R&D capital stock of industry *j* defined as a weighted average of the domestic R&D capital stocks (in industry *j*) of other countries in our sample, using bilateral import shares with the sample countries as weights.[13] The regressions based on the same specification were also carried out using each of technical change and efficiency change as a dependent variable.

Since the foreign R&D capital stock F^j is the import-share-weighted average, it does not reflect the level of imports. Therefore, if productivity gains from the foreign R&D capital stock are related to trade volumes, the above specification may not capture adequately the role of international trade. For this reason, we also estimate a modified version of Equation (4) that accounts for the interaction between foreign R&D capital stocks and the level of imports:

$$M_{i,t+1}^{j} = \alpha_0^j + \alpha_R^j \frac{R_{i,t+1}^j - R_{i,t}^j}{R_{i,t}^j} + \alpha_F^j \lambda_{i,t+1} \frac{F_{i,t+1}^j - F_{i,t}^j}{F_{i,t}^j} \qquad (5)$$

where λ_i stands for the fraction of total imports in GDP. In this equation the elasticity of TFP with respect to the foreign R&D capital stock, $\alpha_F^j \lambda_i$, varies across countries in proportion to their import shares whenever α_F^j is the same for all countries.

The regression results presented in Tables 5 and 6 suggest that productivity gains in such industries as textiles, paper and printing, and non-metallic mineral products depend importantly on domestic R&D spillovers from other industries. In these industries, productivity growth is positively and significantly related to the growth of R&D capital stocks of other industries. It appears that innovation rather than efficiency catch-up tends to depend significantly on domestic R&D spillovers in the paper and printing, and the non-metallic mineral products

[12] For example, see Mansfield et al. (1977).

[13] The bilateral import shares used for the estimation of F^j were calculated for each year based on data of total imports from the IMF's *Direction of Trade Statistics*.

industries whereas domestic spillovers play a key role in efficiency catch-up in the textiles industry. The effect of international R&D spillovers tends to be less pronounced. The link between productivity and foreign R&D capital stocks is found to be positive and significant only in the non-metallic mineral products industry, in which international R&D spillovers appear to contribute to the industry's productivity growth mainly by promoting innovation. In this industry, the elasticity of TFP is greater with respect to international spillovers than with respect to domestic spillovers. However, when trade volume is accounted for, it holds true only for the countries whose import share exceeds at least 16 percent.

V. Conclusions

Previous studies generally find a strong, positive relationship between cumulative R&D and productivity growth, but very few have attempted to incorporate R&D capital explicitly into the analysis of TFP growth. In this paper we consider R&D capital as part of aggregate input proxies in estimating Malmquist TFP indexes for a sample of 14 OECD countries. By doing so, this study sheds light on the extent to which R&D capital formation contributes to output growth. We find the introduction of R&D capital as an additional input reduces our estimate of TFP measure for the OECD countries, on average, by 10 percent. In addition, it is found to be technological progress rather than efficiency catch-up that is driven by the accumulation of R&D capital.

However, the extent of reduction in Malmquist indexes after the introduction of R&D capital input differs across industries as well as countries. We find it is the pace of R&D investment that is significantly related to the extent to which R&D capital formation contributes to output growth. The intensity of R&D investment is found to be irrelevant in this regard. Furthermore, we find productivity gains in manufacturing industries depend importantly on R&D spillovers. In particular, domestic R&D spillovers across industries play a key role in enhancing the productivity of several industries. The beneficial effect of international R&D spillovers within an industry tends to be less pronounced. However, when this effect is found to be significant, it tends to outweigh that of domestic spillovers especially for an economy that is more open to international trade.

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Table 1. R&D Intensity and Growth: Averages 1982-1993 for 14 Countries

	ISIC Code	R&D / Value added	R&D / Capital	R&D growth rate (%)
Total manufacturing	3	0.050	0.346	0.081
Food, beverages and tobacco	31	0.011	0.077	0.074
Textiles, apparel and leather	32	0.007	0.067	0.054
Wood products and furniture [a]	33	0.004	0.035	0.054
Paper, paper products and printing [a]	34	0.006	0.034	0.039
Chemical products	35	0.073	0.415	0.087
Non-metallic mineral products	36	0.016	0.107	0.041
Basic metal industries	37	0.026	0.139	0.034
Fabricated metal products	38	0.086	0.682	0.082

Note: R&D represents R&D expenditures; capital represents gross fixed capital formation.

[a] The corresponding sample period is 1982-1990 due to the classification problem in R&D data of Korea.

Table 2. Productivity Growth, Technical Change and Efficiency Change:
Averages 1982-1993 for 14 Countries

	Inputs: labor and capital			Inputs: labor, capital, and R&D		
	M	TC	EC	M	TC	EC
Total manufacturing	1.040	1.033	1.007	1.036	1.028	1.008
Food, beverages and tobacco	1.039	1.026	1.012	1.033	1.019	1.014
Textiles, apparel and leather	1.033	1.029	1.004	1.021	1.016	1.005
Wood products and furniture	1.035	1.040	0.996	1.014	1.017	0.996
Paper, paper products and printing	1.029	1.022	1.007	1.029	1.020	1.009
Chemical products	1.062	1.069	0.993	1.047	1.061	0.987
Non-metallic mineral products	1.043	1.036	1.007	1.037	1.030	1.008
Basic metal industries	1.027	1.021	1.006	1.016	1.009	1.007
Fabricated metal products	1.020	1.014	1.005	1.019	1.011	1.008

Note: M, TC, and EC represent Malmquist index, technical change, and efficiency change respectively.

Table 3. Average Annual Productivity Growth 1982-1993: Total Manufacturing (ISIC 3)

	Inputs: labor and capital			Inputs: labor, capital, and R&D		
	M	TC	EC	M	TC	EC
Canada	1.062	1.052	1.010	1.050	1.039	1.010
Denmark	1.022	1.015	1.007	1.046	1.034	1.012
Finland	1.053	1.042	1.010	1.056	1.036	1.020
France	1.048	1.046	1.001	1.040	1.036	1.004
Germany	1.013	1.019	0.994	1.032	1.031	1.001
Italy	1.050	1.053	0.997	1.036	1.036	1.000
Japan	1.038	1.048	0.991	1.033	1.037	0.996
Korea	1.075	1.043	1.031	1.006	1.008	0.999
Netherlands	1.068	1.053	1.014	1.055	1.039	1.016
Norway	1.072	1.041	1.030	1.071	1.035	1.035
Spain	0.983	0.983	1.000	0.966	0.966	1.000
Sweden	1.014	1.020	0.995	1.029	1.030	0.999
UK	1.032	1.015	1.017	1.044	1.026	1.017
US	1.039	1.039	1.000	1.037	1.037	1.000
Total	1.040	1.033	1.007	1.036	1.028	1.008

Note: M, TC, and EC represent Malmquist index, technical change, and efficiency change respectively.

Table 4. R&D Intensity and Growth: Effects on R&D Contributions to Output Changes

Industries	Effects of R&D intensity on			Effects of R&D growth on		
	DM	DTC	DEC	DM	DTC	DEC
Total manufacturing	0.766 (1.603)	0.298 (1.131)	0.529 (1.346)	-0.217 (-7.020)	-0.061 (-3.186)	-0.163 (-6.261)
Food, beverages and tobacco	-0.982 (-2.220)	0.641 (1.176)	-1.578 (-3.081)	-0.010 (-1.529)	-0.015 (-1.939)	0.005 (0.606)
Textiles, apparel and leather	-0.419 (-0.352)	-0.244 (-0.192)	-0.172 (-0.382)	-0.052 (-10.596)	-0.051 (-9.315)	-0.001 (-0.277)
Wood products and furniture	-6.109 (-1.239)	-0.131 (-0.025)	-5.780 (-1.597)	-0.041 (-6.274)	-0.035 (-4.889)	-0.005 (-0.875)
Paper, paper products and printing	-3.303 (-1.786)	-0.913 (-0.591)	-2.205 (-1.050)	-0.027 (-5.026)	-0.006 (-1.212)	-0.022 (-3.361)
Chemical products	-0.008 (-0.067)	0.038 (0.481)	-0.029 (-0.282)	-0.030 (-1.706)	-0.014 (-1.201)	-0.020 (-1.347)
Non-metallic mineral products	-0.006 (-0.025)	-0.066 (-0.156)	0.073 (0.171)	-0.019 (-4.275)	-0.017 (-2.224)	-0.002 (-0.230)
Basic metal industries	-0.135 (-0.367)	0.068 (0.134)	-0.270 (-0.566)	-0.041 (-3.495)	-0.011 (-0.620)	-0.032 (-2.040)
Fabricated metal products	0.402 (1.688)	-0.015 (-0.067)	0.412 (1.474)	-0.192 (-8.216)	-0.029 (-1.077)	-0.167 (-5.494)

Notes: 1) R&D intensity is the ratio of R&D expenditures to value added; R&D growth is the growth rate of R&D expenditures.
2) DM, DTC, and DEC represent differences of Malmquist index, technical change and efficiency change variables respectively. These differences are obtained by subtracting each variable under the two input case (labor and fixed capital stock) from the one under the three input case (labor, fixed capital stock and R&D capital stock). 3) *t*-values are in parentheses.

Table 5. Estimates of Coefficients in Eq. (4)

Industries	M		TC		EC	
	α_R^j	α_F^j	α_R^j	α_F^j	α_R^j	α_F^j
Food, beverages and tobacco	-0.112 (-1.244)	0.076 (0.624)	0.017 (0.509)	-0.012 (-0.262)	-0.128 (-1.476)	0.088 (0.751)
Textiles, apparel and leather	0.188 (2.119)	0.093 (0.675)	0.022 (0.368)	0.002 (0.018)	0.159 (2.146)	0.090 (0.776)
Wood products and furniture	-0.030 (-0.152)	0.073 (0.457)	0.452 (3.147)	0.023 (0.194)	-0.472 (-3.271)	0.044 (0.372)
Paper, paper products and printing	0.546 (4.957)	-0.016 (-0.210)	0.319 (3.979)	0.022 (0.384)	0.208 (1.939)	-0.045 (-0.583)
Chemical products	0.024 (0.252)	-0.016 (-0.091)	0.204 (2.919)	0.071 (0.545)	-0.179 (-1.877)	-0.084 (-0.471)
Non-metallic mineral products	0.190 (1.654)	0.307 (2.915)	0.199 (3.363)	0.349 (6.423)	-0.018 (-0.154)	-0.043 (-0.390)
Basic metal industries	-0.053 (-0.226)	-0.121 (-0.393)	-0.253 (-1.933)	-0.051 (-0.298)	0.193 (1.137)	-0.055 (-0.248)
Fabricated metal products	-0.392 (-3.257)	0.175 (1.803)	-0.097 (-1.040)	0.334 (4.438)	-0.321 (-2.587)	-0.155 (-1.550)

Notes: 1) M, TC, and EC represent Malmquist index, technical change, and efficiency change respectively.
2) *t*-values are in parentheses.

Table 6. Estimates of Coefficients in Eq. (5)

Industries	M		TC		EC	
	α_R^j	α_F^j	α_R^j	α_F^j	α_R^j	α_F^j
Food, beverages and tobacco	-0.121 (-1.305)	0.378 (0.738)	0.011 (0.327)	0.056 (0.290)	-0.130 (-1.464)	0.315 (0.643)
Textiles, apparel and leather	0.180 (1.943)	0.397 (0.667)	0.021 (0.333)	0.026 (0.063)	0.153 (1.970)	0.363 (0.726)
Wood products and furniture	-0.059 (-0.298)	-0.052 (-0.074)	0.433 (2.977)	-0.123 (-0.239)	-0.482 (-3.294)	0.051 (0.098)
Paper, paper products and printing	0.552 (4.943)	-0.005 (-0.016)	0.324 (3.999)	0.136 (0.546)	0.208 (1.908)	-0.174 (-0.520)
Chemical products	0.020 (0.206)	0.228 (0.300)	0.198 (2.809)	0.471 (0.831)	-0.177 (-1.839)	-0.230 (-0.297)
Non-metallic mineral products	0.191 (1.588)	1.162 (2.517)	0.194 (3.065)	1.361 (5.605)	-0.013 (-0.102)	-0.202 (-0.422)
Basic metal industries	-0.065 (-0.274)	-0.203 (-0.146)	-0.268 (-2.007)	0.095 (0.122)	0.193 (1.115)	-0.200 (-0.197)
Fabricated metal products	-0.408 (-3.351)	0.778 (1.919)	-0.133 (-1.427)	1.541 (4.973)	-0.302 (-2.408)	-0.743 (-1.778)

Notes: 1) M, TC, and EC represent Malmquist index, technical change, and efficiency change respectively.
2) *t*-values are in parentheses.