PRODUCTIVITY GROWTH AND THE WORLD TECHNOLOGY GAP

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ANDREA FILIPPETTI*§

and

ANTONIO PEYRACHE$^{\Sigma}$

*Italian National Research Council – CNR – IRPPS
§Birkbeck College – University of London
(a.filippetti@irpps.cnr.it)

ΣCentre for Efficiency and Productivity Analysis (CEPA)
School of Economics, The University of Queensland - Australia
(a.peyrache@uq.edu.au)

Abstract

This paper uses a nonparametric approach to investigate the sources of growth in labor productivity for 77 countries and to decompose it in the following three components: (1) total factor productivity; (2) capital deepening; and (3) technological capabilities accumulation (a proxy of the technology gap). We find that the technology gap accounts for a significant share of growth and explains a substantial portion of TFP differences across countries.

JEL code: E23; O33; O47

Keywords – productivity growth; technology gap; technological capabilities; cross-country comparison; Malmquist; DEA.

I. Introduction

Recently there has been a resurgence of interest in cross-country differences in aggregate labor productivity. Some studies argue that capital deepening plays the most prominent part in explaining output per capita growth differences across countries (Kumar and Russell, 2002). Other contributions point to the role played by total factor productivity (TFP) (Caselli, 2005; Easterly and Levin, 2001; Hall and Jones, 1999; Prescott, 1997). Easterly and Levin (2001) conclude that *"the residual (TFP) rather than factor accumulation accounts for most of the income and growth differences across nations*". An older literature, dating back to Gerschenkron (1962), emphasizes the importance of technology transfer and the role of absorptive capacity in fostering growth (Abramovitz, 1986). In that spirit, a lot of attention has been devoted to the role played by technology in explaining economic growth and world disparities in income growth rates (Fagerberg, 1994). Quah (1997) shows that technological diffusion is the main driver leading to increasing polarization and the emergence of clubs (see also Barro and Sala-i-Martin, 2005). Acemoglu and Zilibotti (2001) argue that technology-skill mismatch could account for a large fraction of the observed labor productivity differences across countries.

Following this stream of research, we aim to explore the contribution of the technology gap to labor productivity growth and TFP differences. We introduce the concept of *technological capabilities* to give account of countries' technology gap. The concept of technological capabilities, initially put forward to explain the success of the South Asian countries, has been lately more broadly conceptualized as a set of necessary capabilities for countries to manage technology (Goto and Suzuki, 1989; Kogut and Chang, 1991; Lall, 1992). Both the generation and adoption of technology imply a process of learning. In order to learn, an economic system needs to have specific capabilities, such as the capacity to innovate the business sector, a sufficient research activity, as well as a qualified stock of human capital and physical capital. As such, technological capabilities are not a direct measure of technology, they rather represent the *conditio sine qua non* for countries to generate and adopt technology. This research is conceptually linked to the notion of absorptive capacity, where the idea is that a country needs to have a certain type and level of knowledge and skills to successfully adopt foreign technology (Cohen and Levinthal, 1989; Griffith, et al., 2004; Nelson and Phelps, 1966).

We estimate the world production frontier using a nonparametric method and then decompose labor productivity growth in the following two components: gross total factor productivity (TFP), and capital deepening. In order to investigate TFP differences across countries we further decompose gross TFP into two factors: net TFP and technological capabilities accumulation (the technology gap). A sample including 77 countries for the 1993-2007 period is used. Our nonparametric approach is flexible enough to accommodate cross-countries heterogeneity which has been recognized as a major problem when addressing convergence using standard cross-country regression models (Durlauf, et al., 2005). We show that the technology gap accounts for a significant share of productivity growth and explains a substantial portion of TFP differences across countries. The next section describes the empirical strategy and presents the data. Section 3 discusses the empirical results and concludes.

II. Methodology and data

II.1. The production model

GDP production is modeled using a nonparametric production function where GDP is considered the output and capital and labor the inputs. We add three conditioning variables (innovation capabilities, codified research generation, and education) which are treated as proxy for the level of technological capabilities. We collect these variables in a 3-dimensional vector $\mathbf{Z} \in R^3$. The production technology is conditional on the observed level of the three conditioning variables ($\mathbf{Z} \in R^3$) and is given by all the possible combinations of capital and labor able to produce a given level of output (GDP), conditional on $\mathbf{Z} \in R^3$, at time t. This technological relationship can be represented in a functional form by the output distance function[1]:

$$D_o(Y, K, L \mid \mathbf{Z}, t) = \min_{\theta} \left\{ \theta > 0 : \left(\frac{Y}{\theta}, K, L \right) \in T(\mathbf{Z}, t) \right\} \leq 1 \qquad (1)$$

[1] The production function can be recovered easily from the output distance function:

$$F(K, L \mid \mathbf{Z}, t) = \frac{Y}{D_o(Y, K, L \mid \mathbf{Z}, t)}$$

We use the output distance function due to its generality and flexibility to accommodate multi-output technologies. The reader used to thinking via a production function could find the previous equation useful.

$T(\mathbf{Z},t)=\{(Y,K,L)\in R_{+}^{3}:(K,L)\, can\ produce\, Y,\ given\, \mathbf{Z}\ and\ t\}$. The previous specification means that our model accommodates two important phenomena: *first*, the possibility that a country is lagging behind with respect to the international production frontier (i.e. it is inefficient); *second*, it incorporates explicitly the role of technological capabilities in the production model through the introduction of the conditioning variables Z (i.e. technology gap). What these assumptions mean is that two countries with the same level of capital and labor can produce very different output levels according to their level of technological capabilities and efficiency of production. We assume the following monotonicity conditions of the output distance function:

1. Non-decreasing in output: $D_o(Y_0,K,L\mid \mathbf{Z},t)\leq D_o(Y_1,K,L\mid \mathbf{Z},t)$, $Y_0\leq Y_1$;

2. Non-increasing in inputs: $D_o(Y,K_0,L_0\mid \mathbf{Z},t)\geq D_o(Y,K_1,L_1\mid \mathbf{Z},t)$, $K_0\leq K_1$, $L_0\leq L_1$;

3. Non-increasing in the Z's: $D_o(Y,K,L\mid \mathbf{Z}_0,t)\geq D_o(Y,K,L\mid \mathbf{Z}_1,t)$, $\mathbf{Z}_0\leq \mathbf{Z}_1$.

Since this is a macroeconomic comparison framework we follow the standard practice of assuming constant returns to scale (CRS). With the CRS assumption the production function becomes homogeneous of degree -1 in inputs (Fare and Primont, 1995). An additional assumption is made, imposing that the Z's are separable from the input-output vector:

$$D_o(Y,K,L\mid \mathbf{Z},t)=\frac{1}{H(\mathbf{Z},t)}\cdot D_o(Y,K,L\mid t) \tag{2}$$

This means that the technology gap is a Hicks neutral shift in the production technology. Following Daraio and Simar (2005), the magnitude of the impact of the Z-variables onto the production process can be accounted for as:

$$\frac{D_o(Y,K,L)}{D_o(Y,K,L\mid \mathbf{Z},t)}=H(\mathbf{Z}) \tag{3}$$

This measure is intrinsically static, but a dynamic measure can be obtained very easily. Since the technology is homothetic in Z, gross total factor productivity change (GTFP) can be measured by the Malmquist index (Fare, et al., 1994):

$$GTFP=\left(\frac{D_o(Y^{t+1},K^{t+1},L^{t+1}\mid t)}{D_o(Y^{t},K^{t},L^{t}\mid t)}\frac{D_o(Y^{t+1},K^{t+1},L^{t+1}\mid t+1)}{D_o(Y^{t},K^{t},L^{t}\mid t+1)}\right)^{\frac{1}{2}} \tag{4}$$

One can account for the effect of capital deepening considering the differential between labor productivity change and GTFP: $\frac{y^{t+1}}{y^t} = GTFP \cdot KD$. This last relationship implicitly defines the following capital deepening effect (KD):

$$KD = \left(\frac{D_o\left(y^t, k^t, 1 \mid t\right)}{D_o\left(y^t, k^{t+1}, 1 \mid t\right)} \frac{D_o\left(y^{t+1}, k^t, 1 \mid t+1\right)}{D_o\left(y^{t+1}, k^{t+1}, 1 \mid t+1\right)} \right)^{\frac{1}{2}} \tag{5}$$

where $y^t = \frac{Y^t}{L^t}$ $k^t = \frac{K^t}{L^t}$. To obtain the net TFP growth one should account for the growth in Z. This can be done using the following index:

$$ZCC = \left(\frac{H\left(\mathbf{Z}^{t+1}, t\right)}{H\left(\mathbf{Z}^t, t\right)} \frac{H\left(\mathbf{Z}^{t+1}, t+1\right)}{H\left(\mathbf{Z}^t, t+1\right)} \right)^{\frac{1}{2}} \tag{6}$$

This index takes a value equal to one if $\mathbf{Z}^t = \mathbf{Z}^{t+1}$ and different from one if $\mathbf{Z}^t \neq \mathbf{Z}^{t+1}$. In this second event the index will be larger than one if the overall impact of the change in technological capabilities has been positive and smaller than one otherwise. A net total factor productivity index (NTFP) is defined as:

$$NTFP = \left(\frac{D_o\left(Y^{t+1}, K^{t+1}, L^{t+1} \mid \mathbf{Z}^{t+1}, t\right)}{D_o\left(Y^t, K^t, L^t \mid \mathbf{Z}^t, t\right)} \frac{D_o\left(Y^{t+1}, K^{t+1}, L^{t+1} \mid \mathbf{Z}^{t+1}, t+1\right)}{D_o\left(Y^t, K^t, L^t \mid \mathbf{Z}^t, t+1\right)} \right)^{\frac{1}{2}} \tag{7}$$

It is easy to verify that, due to the homothetic assumption, the ratio of the GTFP to the ZCC returns the NTFP: $NTFP = GTFP / ZCC$. The product of the three components (NTFP, ZCC and KD) returns a decomposition of output per worker growth:

$$\frac{Y^{t+1} / L^{t+1}}{Y^t / L^t} = NTFP \cdot ZCC \cdot KD = GTFP \cdot KD \tag{8}$$

Thus we impute GDP per worker growth to Gross TFP and capital deepening and provide an additional decomposition of TFP into net total factor productivity growth (NTFP) and technological capabilities change (ZCC) (the technology gap). This allows us to explore the portion of gross TFP accounted for by the technological capabilities.

II.2. Data

Table 1 summarizes the data collected for the empirical analysis. GDP is at constant prices and deflated by PPP's. GDP per worker is our dependent variable, and represents a standard measure for labor productivity (see Kumar and Russell, 2002 among others). The stock of capital has been built using the permanent inventory method, while labor is measured as the number of people employed. As already explained, technological capabilities are the *conditio sine qua non* for countries to generate and adopt technology. The combination of technological capabilities will vary depending on the stage of development of a country and on its specific industrial structure. We therefore take into consideration three different dimensions, customary in this literature, to account for technological capabilities: (i) innovation capability; (ii) codified knowledge generation; and (iii) education.

Patent is a standard measure of innovation output and has been broadly used in order to measure innovation (Griliches, 1990). As such, it can be considered a "tolerable assumption" of the innovative capabilities of the business sector (Schmookler, 1962). The variable "scientific and technical articles" represents the magnitude of the generation of codified knowledge and has been often used in composite indicators addressing technological capabilities (Archibugi and Coco, 2004). Specifically, it reflects the knowledge generated in the universities and public-funded research centres. We take it as a proxy of the wealth of the research system. Finally, public expenditure in education accounts for investment in the education system.

[TABLE 1]

III. Results and final remarks

Table 2 displays the results of the decomposition of labor productivity growth for all the 77 countries over the period 1993-2007. The overall results provide evidence of a relevant contribution played by both capital deepening and TFP, accounting respectively for the 46% and 54% of output per worker growth. This contrasts with other results, such as Kumar and Russell (2002), who find that most of the worldwide productivity growth is attributable to capital deepening. This is due to the fact that our data refer to a more recent period . In the period under scrutiny here, several countries have started to emerge (e.g. Asian countries and Transition Economies). As we show below, this is accounted for mainly by an increase in TFP in opposition to capital deepening, thus explaining the higher relative contribution of TFP observed in our results.

Table 2 also shows the results of the decomposition of the change in gross TFP into net TFP and technological capabilities growth (ZCC). It arises that with an average annual growth rate of 1.7%, technological capabilities accumulation explains most TFP change. This strongly supports the case for our initial intuition of using technological capabilities as a direct measure of the technology gap.

[TABLE 2]

Table 3 shows the same results limited to some selected groups of countries. In terms of the magnitude of the average labor productivity growth over the period 1993-2007, China (8.9%) is the leader, followed by India (4.9%), the Transition Economies (4.6%) and the Asian Tigers (3.2%). In terms of relative contribution of the different component to growth, capital deepening, in opposition to TFP change, seems to have made an important contribution for the more advanced countries and China: specifically, the contribution of capital deepening accounts for the 88%, 72% and 70% of labor productivity growth for the industrialized countries, the Asian Tigers and China respectively. These results for China can be easily explained by the spectacular boost in investment over the last fifteen years which came to account for almost 40% of total GDP. By contrast, the role of TFP change, *via technological capabilities accumulation,* is prominent in Transition Economies, backward countries, as well as for some large emerging countries such as India, Indonesia, and Brazil.

[TABLE 3]

Summing up, technological capabilities (as a proxy for the technology gap) are an important driver of labor productivity growth and cross-country TFP differences. Our results seem to support the case for this choice. On the one hand, consistently with other studies we find that capital deepening is a key source of growth for more advanced countries. On the other hand, we show that the technology gap (as proxied by innovation capabilities of firms, the generation of codified knowledge, and investment in human capital) accounts for a substantial share of labor productivity growth and differences in TFP growth.

Tables and Figures

TABLE 1 - THE VARIABLES AND SOURCES

	Variable	Sources
GDP per worker:	GDP (PPP, constant prices)	Penn World Table
	Labor force	Penn World Table
Capital deepening	Fixed capital (build with the permanent inventory method)	Penn World Table
Technological capabilities accumulation (Z)	Patents application in the United States Patent Office	USPTO
	Articles published in scientific journals	WDI (World Bank)
	Public expenditure on education	WDI (World Bank)

TABLE 2 - DECOMPOSITIONS RESULTS WITH 1993-2007 AVERAGE, (77 COUNTRIES).

Country	output per worker 1993	output per worker 2007	output per worker growth (KD+GTFP)	contribution to change in output per worker: capital deepening	Gross TFP (ZCC+NTFP)	ZCC	Net TFP
Albania	6,514	14,245	5.6	0.4	5.2	5.6	-0.4
Algeria	19,018	17,589	-0.6	-2.0	1.5	2.0	-0.5
Argentina	23,381	26,138	0.8	0.1	0.7	0.6	0.1
Australia	51,807	67,207	1.9	1.9	-0.1	0.4	-0.4
Austria	56,143	69,138	1.5	1.0	0.5	0.4	0.1
Bangladesh	1,663	2,477	2.8	1.7	1.1	1.7	-0.6
Belgium	62,717	74,879	1.3	1.3	0.0	0.4	-0.5
Bolivia	7,324	8,408	1.0	0.0	1.0	2.0	-1.0
Brazil	16,056	17,773	0.7	-0.2	0.9	0.6	0.3
Bulgaria	13,230	21,187	3.4	-0.1	3.5	3.0	0.5
Cameroon	4,758	5,083	0.5	-0.9	1.4	1.5	-0.1
Canada	50,805	65,217	1.8	1.5	0.3	0.0	0.2
Chile	20,461	29,844	2.7	3.3	-0.6	1.8	-2.4
China	2,638	8,690	8.5	6.0	2.5	1.5	1.1
Costa Rica	18,319	22,230	1.4	1.1	0.3	2.1	-1.8
Croatia	18,169	35,104	4.7	2.1	2.6	3.0	-0.4
Czech Republic	29,239	45,317	3.1	1.5	1.6	2.6	-1.0
Denmark	46,606	64,478	2.3	2.5	-0.2	0.3	-0.5
Ecuador	15,571	16,652	0.5	-0.4	0.9	3.2	-2.3
Egypt, Arab Rep.	10,989	14,767	2.1	1.4	0.7	2.2	-1.5
Estonia	14,320	38,007	7.0	2.6	4.4	4.7	-0.3
Ethiopia	1,068	1,573	2.8	0.0	2.8	2.2	0.6
Finland	41,318	65,417	3.3	1.0	2.3	0.5	1.8
France	56,917	69,014	1.4	1.1	0.3	0.1	0.2
Germany	54,660	64,692	1.2	0.9	0.3	0.0	0.3
Ghana	2,323	2,827	1.4	0.0	1.4	2.6	-1.2
Greece	42,493	58,178	2.2	1.3	0.9	1.1	-0.2
Hong Kong	55,273	74,905	2.2	2.0	0.2	0.9	-0.7
Hungary	24,740	41,848	3.8	2.7	1.0	1.4	-0.3
Iceland	40,616	58,945	2.7	1.8	0.8	3.9	-3.1
India	3,392	6,621	4.8	3.0	1.8	1.4	0.4
Indonesia	5,822	7,126	1.4	0.5	0.9	2.0	-1.1
Iran, Islamic Rep.	23,393	26,534	0.9	-0.5	1.4	2.6	-1.2
Ireland	47,928	81,673	3.8	2.1	1.7	1.6	0.2
Israel	50,265	60,219	1.3	1.1	0.2	0.6	-0.4
Italy	59,565	68,952	1.0	1.4	-0.4	0.1	-0.4
Jamaica	14,231	15,925	0.8	1.6	-0.8	-1.6	0.9
Japan	50,604	60,538	1.3	1.1	0.2	0.0	0.2
Jordan	12,478	15,277	1.4	-0.4	1.8	2.2	-0.4
standard deviation			1.7	1.4	1.3	1.4	1.1
Mean			**2.4**	**1.1**	**1.2**	**1.7**	**-0.4**

Country	output per worker 1993	output per worker 2007	output per worker growth (KD+GTFP)	contribution to change in output per worker: capital deepening	Gross TFP (ZCC+NTFP)	ZCC	Net TFP
Kenya	3,000	3,085	0.2	0.2	0.0	2.1	-2.1
Korea, Rep.	29,557	49,590	3.7	3.0	0.7	0.8	-0.1
Latvia	10,806	29,298	7.1	4.8	2.3	3.5	-1.2
Lebanon	27,093	30,197	0.8	-2.2	3.0	4.3	-1.4
Lithuania	14,767	33,401	5.8	3.0	2.8	4.3	-1.5
Luxembourg	110,389	163,736	2.8	1.3	1.5	3.2	-1.7
Malaysia	20,584	29,478	2.6	1.8	0.7	1.5	-0.8
Mexico	27,725	30,702	0.7	0.8	-0.1	0.6	-0.7
Morocco	7,960	10,345	1.9	1.5	0.4	0.8	-0.4
Netherlands	57,728	69,648	1.3	1.0	0.4	0.3	0.1
New Zealand	39,031	47,308	1.4	1.5	-0.1	1.1	-1.2
Nigeria	4,765	5,856	1.5	-0.5	1.9	3.4	-1.5
Norway	68,289	90,345	2.0	1.2	0.8	0.5	0.3
Pakistan	6,333	7,022	0.7	0.0	0.8	2.4	-1.6
Peru	11,223	15,725	2.4	0.6	1.8	0.5	1.3
Philippines	5,802	7,663	2.0	0.4	1.6	1.4	0.2
Poland	17,360	34,310	4.9	2.4	2.5	1.2	1.2
Portugal	33,849	40,070	1.2	2.0	-0.8	1.3	-2.1
Romania	11,695	21,700	4.4	0.0	4.4	3.4	1.0
Russian Federation	18,886	26,018	2.3	-2.2	4.5	0.9	3.6
Singapore	54,080	88,952	3.6	1.7	1.8	1.7	0.2
Slovak Republic	19,976	38,938	4.8	0.7	4.0	4.0	0.1
Slovenia	34,618	51,204	2.8	1.9	0.9	2.6	-1.7
South Africa	23,077	24,637	0.5	-0.1	0.5	0.1	0.5
Spain	49,125	57,919	1.2	1.3	-0.1	0.4	-0.5
Sri Lanka	5,676	9,629	3.8	2.0	1.8	3.1	-1.4
Sweden	44,187	63,261	2.6	1.0	1.6	0.2	1.4
Switzerland	56,043	66,193	1.2	0.7	0.5	0.2	0.3
Thailand	8,879	12,887	2.7	1.2	1.5	1.5	-0.1
Tunisia	14,023	19,535	2.4	0.1	2.3	1.9	0.3
Turkey	24,341	34,960	2.6	2.1	0.4	3.1	-2.7
Uganda	1,362	2,356	3.9	0.5	3.4	4.7	-1.3
Ukraine	11,739	13,203	0.8	-0.5	1.4	0.9	0.5
United Kingdom	48,070	67,203	2.4	2.1	0.3	0.1	0.2
United States	63,534	82,803	1.9	2.2	-0.4	0.0	-0.4
Uruguay	18,155	21,958	1.4	0.7	0.6	1.9	-1.3
Venezuela, RB	27,775	25,484	-0.6	-1.0	0.4	0.3	0.0
Vietnam	2,225	4,697	5.3	4.2	1.1	3.4	-2.2

TABLE 3 - Decompositions results with 1993-2007 average, (selected countries).

Country	output per worker 1993	output per worker 2007	output per worker growth	contribution to change in output per worker: capital deepening	Gross TFP	ZCC	Net TFP
industrialized countries	52,250	66,646	1.7	1.4	0.3	0.4	-0.1
Asian Tigers	46,303	71,149	3.1	2.3	0.9	1.1	-0.2
Transition economies	17,475	32,136	4.5	1.7	2.8	3.1	-0.3
China	2,638	8,690	8.5	6.0	2.5	1.5	1.1
India	3,392	6,621	4.8	3.0	1.8	1.4	0.4
Indonesia	5,822	7,126	1.4	0.5	0.9	2.0	-1.1
South Africa	23,077	24,637	0.5	-0.1	0.5	0.1	0.5
Brazil	16,056	17,773	0.7	-0.2	0.9	0.6	0.3
Russian Federation	18,886	26,018	2.3	-2.2	4.5	0.9	3.6
backward countries	20,656	28,977	3.1	1.4	1.7	1.2	0.5

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APPENDIX

Since we deal with a balanced panel dataset, for each time period we can collect all the observed outputs into a Kx1 vector $\mathbf{Y}^t$, all the observed inputs into a Kx2 matrix $\mathbf{X}^t = [\mathbf{K}^t, \mathbf{L}^t]$ and all the observed external variables into a Kx3 matrix $\mathbf{Z}^t$. The technology set is defined as the convex linear envelope of the data at each point in time (DEA):

$$T(\mathbf{X}^t, \mathbf{Y}^t, \mathbf{Z}^t) = \{(y, \mathbf{x}, \mathbf{z}) : y \le \boldsymbol{\lambda}\mathbf{Y}^t, \mathbf{x} \ge \boldsymbol{\lambda}\mathbf{X}^t, \mathbf{z} \ge \boldsymbol{\lambda}\mathbf{Z}^t, \boldsymbol{\lambda} \ge \mathbf{0}\}$$

The output distance function is calculated using the DEA technology. For every time period the following K linear programs are solved for computing the actual distance functions at each time period for each observation (this means solving KxT linear programs). The linear programs for GTFP are ($k = 1,...,K$):

$$\begin{aligned} &\frac{1}{D_o(Y_k^t, K_k^t, L_k^t, t)} = \max\theta \\ &st \quad \theta y_k^t \le \boldsymbol{\lambda}\mathbf{Y}^t \\ &\qquad \mathbf{x}_k^t \ge \boldsymbol{\lambda}\mathbf{X}^t \\ &\qquad \boldsymbol{\lambda} \ge \mathbf{0} \end{aligned} \quad , \quad \begin{aligned} &\frac{1}{D_o(Y_k^{t+1}, K_k^{t+1}, L_k^{t+1}, t)} = \max\theta \\ &st \quad \theta y_k^{t+1} \le \boldsymbol{\lambda}\mathbf{Y}^t \\ &\qquad \mathbf{x}_k^{t+1} \ge \boldsymbol{\lambda}\mathbf{X}^t \\ &\qquad \boldsymbol{\lambda} \ge \mathbf{0} \end{aligned} \quad , \quad \begin{aligned} &\frac{1}{D_o(Y_k^t, K_k^t, L_k^t, t+1)} = \max\theta \\ &st \quad \theta y_k^t \le \boldsymbol{\lambda}\mathbf{Y}^{t+1} \\ &\qquad \mathbf{x}_k^t \ge \boldsymbol{\lambda}\mathbf{X}^{t+1} \\ &\qquad \boldsymbol{\lambda} \ge \mathbf{0} \end{aligned}$$

Homotheticity is imposed following the Primont and Primont (1994) method and taking the geometric mean across all the possible input-output isoquants. The linear programs associated to this procedure are:

$$\begin{aligned} &\frac{1}{D_o(Y_i^t, K_i^t, L_i^t, Z_k^t, t)} = \max\theta \\ &st \quad \theta y_i^t \le \boldsymbol{\lambda}\mathbf{Y}^t \\ &\qquad \mathbf{x}_i^t \ge \boldsymbol{\lambda}\mathbf{X}^t \\ &\qquad \mathbf{z}_k^t \ge \boldsymbol{\lambda}\mathbf{Z}^t \\ &\qquad \boldsymbol{\lambda} \ge \mathbf{0} \end{aligned} \quad , \quad i,k = 1,...,K$$