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Meta-frontier analysis of technology gap for efficiency and productivity comparisons across different sub-groups of EU-27 countries

Christina Bampatsou
Ionian University

George Halkos
University of Thessaly

Abstract

This paper adopts the Data Envelopment Analysis (DEA) to measure technical efficiency (TE), technical efficiency change (TEC) and technical change (TC) scores across four sub-groups of EU-27 countries for the period 1995-2019. Then metafrontier frameworks are used to evaluate technological gap ratio (TGR) and also catch-up effect achieved by each Group of EU-27 countries. In the last step we conduct a bootstrap second stage regression analysis by highlighting the influence of different variables on both efficiency scores and TGR values.

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Contact: Christina Bampatsou - c.bampatsou@ionio.gr, George Halkos - halkos@econ.uth.gr.
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1. Introduction

Several papers have introduced the metafrontier efficiency analysis for either cross-sectional or panel data (Chen *et al.*, 2020; Ma *et al.*, 2018; Kounetas and Napolitano 2018; Afsharian, 2017) in order to overcome the deficiency of traditional DEA method related to Decision Making Units (DMUs) evaluation under a unified technical environment.

Our study may enrich the specific literature by providing production frontier models with both cross-sectional and panel data approaches across different sub-groups of EU-27 countries. Furthermore, to the best of our knowledge, there is no comparable study that investigates the TE and TGR scores related to the level of environmental degradation (CO_2 emissions), population density, population growth, industrialization and urbanization, through a two-stage procedure proposed by Simar and Wilson (2007). The method of Simar and Wilson is based on boostrap techniques that allow correcting the biases in DEA efficiency scores due to sampling variation. In other words, the method yields a statistically reliable result that indicates whether increases or decreases in productivity are significant in a statistical sense.

2. Data and methodology

In the present study we utilize the total labor force, capital stock at constant 2017 national prices (in millions 2017 US$) and energy use (kg of oil equivalent) as inputs while gross domestic product (GDP, expressed in constant 2010 US$) is used as output to determine both TE and Malmquist productivity index across four sub-groups (Group 1, Group 2, Group 3, Group 4) of EU-27 countries for period 1995-2019. Then, through DEA bootstrap approach of Simar and Wilson (2007) the variables of CO_2 emissions (kt), population density (people per sq. km of land area), industry (current US$), population growth (annual %) and urban population are used as independent variables (see Table 1. 1 in Appendix 1) in the second stage regression analysis.

Group of countries are sorted according to their 2018-19 average volume index per capita for GDP (see Table 1. 2 in Appendix 1). Taking into consideration that economic growth is utilized as an output variable of our model the Eurostat classification that indicates the relative volumes of GDP per capita (Eurostat, 2021) was regarded as a determinant in country classification system that succeeds to adjust for differences in price levels. Failing to do so would result in an overestimation of GDP and therefore efficiency and productivity levels for countries with high price levels, relative to countries with low price levels within heterogeneous groups.

The source for labor force, energy use, GDP, CO_2 emissions, population density, industry, population growth and urban population data is the World Bank (World Bank, 2021) and for the capital stock data the Penn World Table, version 10.0 (Feenstra *et al.*, 2015).

2.1 DEA metafrontier analysis on output oriented TE

Assuming there is a production technology defined as capability transforming a vector of inputs into a vector of outputs, we first presume there are K=4 technology Groups of DMUs $\left(S_{Group_k}\right)$ included in the analysis. The Group specific technology for each k=1, 2, 3, 4 can be defined as:

$$S_{Group_k} = \{(\mathbf{x}, \mathbf{y}) : \mathbf{x} \geq \mathbf{0}; \mathbf{y} \geq \mathbf{0}; \mathbf{x} \text{ can be used by dmus in group } k \text{ to produce } \mathbf{y}\} \quad (1)$$

Here we focus on output orientated DEA models, assuming constant (CRS) and variable (VRS) returns to scale.

In that connection, output-oriented output sets for each k=1, 2, 3, 4 can be expressed as:

$$P_{Group_k}(\mathbf{x}) = \left\{ \mathbf{y} : (\mathbf{x}, \mathbf{y}) \in S_{Group_k} \right\} \tag{2}$$

under the properties of the output set (Coelli *et al.*, 2005):

a. $0 \in \mathrm{P}(\mathrm{x})$ (inactivity);

b. If $\mathrm{y} \in \mathrm{P}(\mathrm{x})$ then $\mathrm{y}^* = \theta \mathrm{y} \in \mathrm{P}(\mathrm{x})$ for all $0 < \theta \leq 1$ $(\text{weak disposability})$;

c. $\mathrm{P}(\mathrm{x})$ is a closed and bounded set; and

d. $\mathrm{P}(\mathrm{x})$ is a convex set.

Thus, output-oriented distance functions and TGRs for each k=1, 2, 3, 4 are defined as:

$$D_{Group_k}(\mathbf{x}, \mathbf{y}) = \inf_\theta \left\{ \theta > 0 : (\mathbf{y}/\theta) \in P_{Group_k}(\mathbf{x}) \right\} \tag{3}$$

$$TGR_{Group_k}(x, y) = \frac{D_{Meta}(x, y)}{D_{Group_k}(x, y)} = \frac{TE_{Meta}(x, y)}{TE_{Group_k}(x, y)} \tag{4}$$

2.2 Estimation and decomposition of Malmquist Productivity Index (M) of Group frontier and metafrontier

Based on Caves *et al.* (1982a, b) a DMU productivity change belonging to a specific Group and regarding period 0 as the base year can be defined as:

$$M^0 = \frac{D^0(x^1, y^1)}{D^0(x^0, y^0)} \tag{5}$$

In this context, productivity change for a DMU belonging to a specific Group and regarding period 1 as the base year is:

$$M^1 = \frac{D^1(x^1, y^1)}{D^1(x^0, y^0)} \tag{6}$$

According to Fare *et al.* (1992, 1994), from period 0 to period 1, output oriented geometric mean of Malmquist productivity index can be expressed as:

$$\mathrm{M}(x^0, y^0, x^1, y^1) = \left[\frac{D^0(x^1, y^1)}{D^0(x^0, y^0)} \times \frac{D^1(x^1, y^1)}{D^1(x^0, y^0)} \right]^{0.5} \tag{7}$$

This index represents the productivity change degree of a DMU during period 0 to 1. It can be decomposed into TC and TEC

$$M(x^0, y^0, x^1, y^1) = \underbrace{\frac{D^1(x^1, y^1)}{D^0(x^0, y^0)}}_{TEC} \underbrace{\left[\frac{D^0(x^1, y^1)}{D^1(x^1, y^1)} \times \frac{D^0(x^0, y^0)}{D^1(x^0, y^0)} \right]^{0.5}}_{TC} \tag{8}$$

If $M \rangle 1$, it represents a productivity rise; if $M \langle 1$, it represents a declining trend.

The Group Malmquist Productivity Index $\left(M_{Group_k} \right)$ can be expressed as:

$$M_{Group_k}(x^0, y^0, x^1, y^1) = \frac{D^1_{Group_k}(x^1, y^1)}{D^0_{Group_k}(x^0, y^0)} \left[\frac{D^0_{Group_k}(x^1, y^1)}{D^1_{Group_k}(x^1, y^1)} \times \frac{D^0_{Group_k}(x^0, y^0)}{D^1_{Group_k}(x^0, y^0)} \right]^{0.5} = TEC_{Group_k} \times TC_{Group_k} \tag{9}$$

The Metafrontier Malmquist Productivity Index (M_{Meta}) can be expressed as:

$$M_{Meta}(x^0, y^0, x^1, y^1) = \frac{D^1_{Meta}(x^1, y^1)}{D^0_{Meta}(x^0, y^0)} \left[\frac{D^0_{Meta}(x^1, y^1)}{D^1_{Meta}(x^1, y^1)} \times \frac{D^0_{Meta}(x^0, y^0)}{D^1_{Meta}(x^0, y^0)} \right]^{0.5} = TEC_{Meta} \times TC_{Meta} \tag{10}$$

The terms of TEC_{Meta} and TC_{Meta} that represent the TEC and TC measured on the basis of the metafrontier, are defined as follows:

$$TEC_{Meta} = \frac{D^1_{Group_k}(x^1, y^1)}{D^0_{Group_k}(x^0, y^0)} \times \frac{TGR^1_{Group_k}(x^1, y^1)}{TGR^0_{Group_k}(x^0, y^0)} = TEC_{Group_k} \times \underbrace{\frac{TGR^1_{Group_k}(x^1, y^1)}{TGR^0_{Group_k}(x^0, y^0)}}_{TGR_{Group_k}} \tag{11}$$

$$TC_{Meta} = TC_{Group_k}\left[\frac{TGR^0_{Group_k}(x^0, y^0)}{TGR^1_{Group_k}(x^0, y^0)} \times \frac{TGR^0_{Group_k}(x^1, y^1)}{TGR^1_{Group_k}(x^1, y^1)}\right]^{0.5} = TC_{Group_k}\underbrace{\left[\frac{TGR^0_{Group_k}(x^0, y^0)}{TGR^1_{Group_k}(x^1, y^1)} \times \frac{TGR^0_{Group_k}(x^1, y^1)}{TGR^1_{Group_k}(x^0, y^0)}\right]^{0.5}}_{\frac{1}{TGR_{Group_k}}} \tag{12}$$

M_{Meta} can then be expressed as:

$$M_{Meta} = M_{Group_k} \times \underbrace{\left[\frac{TGR^1_{Group_k}(x^1, y^1)}{TGR^0_{Group_k}(x^0, y^0)} \times \frac{TGR^0_{Group_k}(x^1, y^1)}{TGR^1_{Group_k}(x^0, y^0)}\right]^{0.5}}_{(catch-up)^{-1}} \tag{13}$$

Thus, the catch-up effect is the ratio of k_{th} Group's production frontier to metafrontier represented as:

$$catch-up = \frac{M_{Group_k}}{M_{Meta}} \tag{14}$$

2.3 Second-stage regression analysis on output oriented TE and TGR

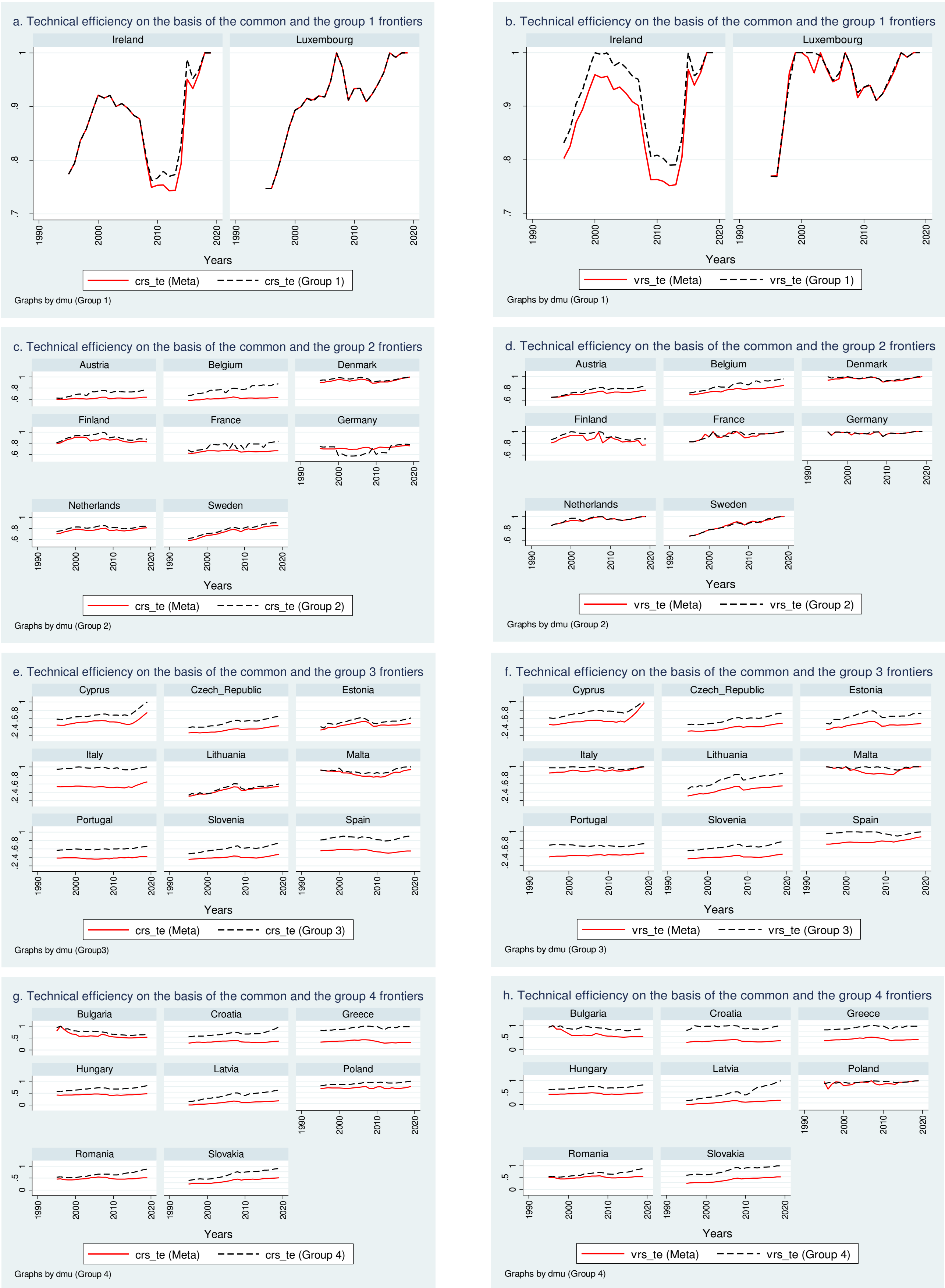
In our second stage the DEA bootstrap approach along the lines of Simar and Wilson (2007) is applied to investigate the relationships between efficiency scores (TE) and TGR values across four sub-groups of EU-27 countries as calculated by DEA based methods, in the first stage of our analysis, and the variables of CO_2 emissions, Population density, Industry, Population growth and Urban population.

3. Empirical results

3.1 Metafrontiers for efficiency comparisons across Groups

When the score of TE is 1, the selected Group of countries are said to be fully efficient regarding the adopted technolgy. Figure 1 reflects that TE when measured with respect to Group frontiers is generally higher than metafrontier TE with the exception of Germany under CRS specification. From Figure 1 there is a substantial divergence, especially among countries' frontiers of Groups 3 and 4, with the lowest GDP per capita, and that of metafrontiers, which was mainly derived from the Group effect of economic development relative to the EU average.

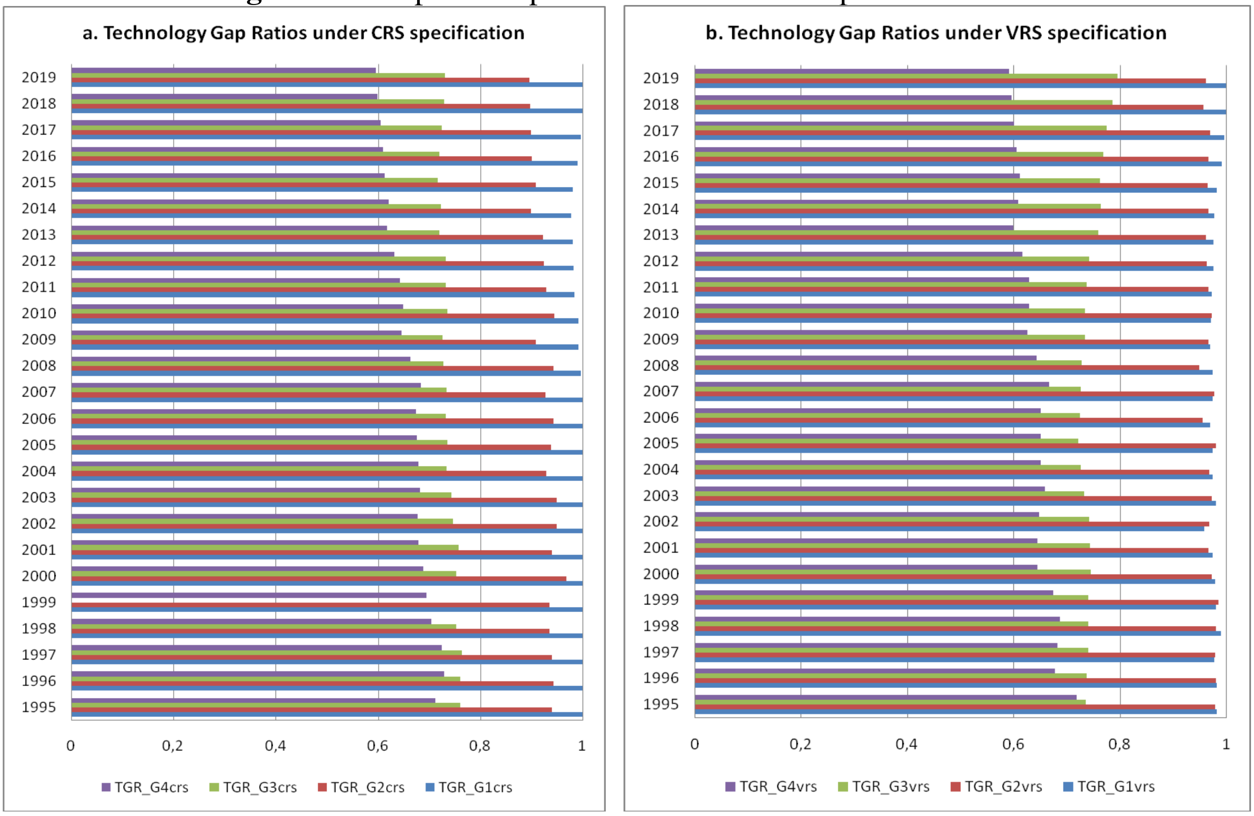
Figure 1. TE per Group and that of metafrontier under CRS and VRS specification



Accordingly, the high-income countries (Groups 1 and 2) have higher TGRs than the ones of Groups 3 and 4, implying there is a small technology gap between actual production technology and potential overall level.

A TGR score of 1 implies there is no gap to fill for the selected Group with respect to the meta-frontier technology. In other words, the closer TGR is to 1, the smaller the technology gap for the Group under consideration regarding the economy modeled (Figure 2).

Figure 2. TGR per Group under CRS and VRS specification



3.2 Metafrontiers and productivity growth

Table I presents a summary of the decompositions of Malmquist Productivity Index of Group frontier and metafrontier and also the catch-up effect for each Group of countries presented at three sub-periods.

Group 1 countries with the highest level of GDP per capita, have the lowest average TGR ratio $\left(\frac{TEC_{Meta}}{TEC_{Group_k}}\right)$ during 1995-2003 (Table I), hence, its average TE is reduced from 100% when compared relative to Group 1 frontier $\left(TEC_{Group_k}\right)$ to 99.3% when compared to EU-27 metafrontier $\left(TEC_{Meta}\right)$. Similarly, from Figure 3 the average value of TGR for Group 1 is less than 1 for period 1995-2019.

It is worth pointing out that in the second and third sub-groups, the respective frontiers are tangent to metafrontier, as the average value of TGR equals to 1, for periods 1995 to 2003 and 2012 to 2019 (Table I) respectively.

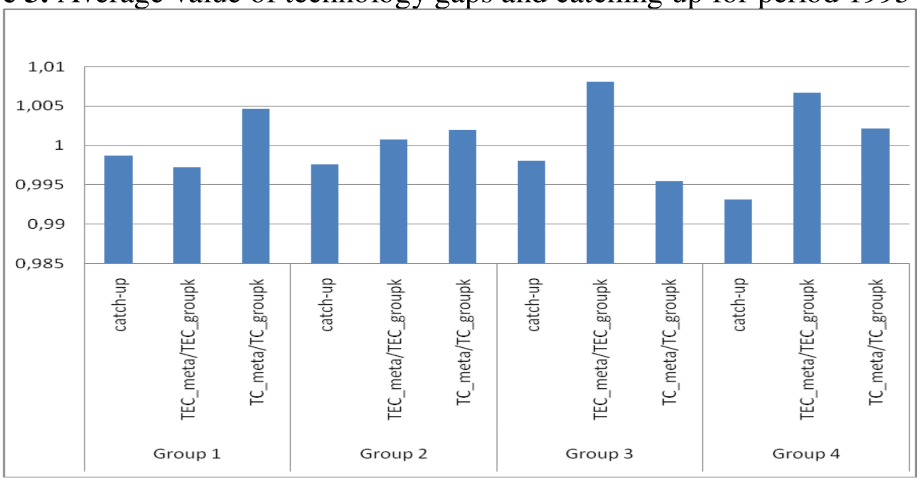
In member states of Group 4 with the lowest level of GDP/c, growth rate from 1995 to 2019 was, on average, between 0.48 and 0.28 percentage points below EU-27 average. From Table I the growth index of TGR between Group 4 frontier and EU-27 metafrontier, is less than 1 only for sub-period 1995-2003. In this period Group 4 is making faster technological progress than EU-27 does. For the next two sub-periods (2004-2011 and 2012-2019), the specific Group has already reached a certain level of technological progress which interpret its slower growth rate compared with EU-27 metafrontier.

Table I. Estimates per Group of both TGR changes and catch-up effect, by sub-periods

Groups	Period	M_{Meta}	TEC_{Meta}	TC_{Meta}	M_{Group_k}	TEC_{Group_k}	TC_{Group_k}	$catch-up$	$\frac{TEC_{Meta}}{TEC_{Group_k}}$	$\frac{TC_{Meta}}{TC_{Group_k}}$
Group 1	1995-2003	0.979	0.993	0.987	0.974	1	0.974	0.995	0.993	1.013
	2004-2011	0.995	1.003	0.992	0.993	1	0.993	0.998	1.003	0.999
	2012-2019	0.97	0.996	0.973	0.972	1	0.972	1.002	0.996	1.001
Group 2	1995-2003	0.99	0.999	0.991	0.986	0.999	0.987	0.996	1	1.004
	2004-2011	0.994	1	0.995	0.994	0.998	0.995	1	1.002	1
	2012-2019	0.995	1.007	0.988	0.993	1.006	0.987	0.998	1.001	1.001
Group 3	1995-2003	0.989	0.997	0.995	0.984	0.985	0.999	0.995	1.012	0.996
	2004-2011	0.994	1.002	0.992	0.993	0.991	1.002	0.999	1.011	0.990
	2012-2019	0.976	0.999	0.978	0.976	0.999	0.978	1	1	1
Group 4	1995-2003	0.989	0.99	1	0.983	0.996	0.987	0.994	0.994	1.013
	2004-2011	0.999	1.007	0.993	0.994	0.997	0.997	0.995	1.010	0.996
	2012-2019	0.99	1.007	0.984	0.98	0.993	0.988	0.990	1.014	0.996

As shown in Figure 3, the average annual rate of catch-up effect $\left(\frac{M_{Group_k}}{M_{Meta}}\right)$ is less than unity for all Groups of countries indicating in each case, the Group total factor productivity is catching with EU-27 total factor productivity from period 0 to 1.

Figure 3. Average value of technology gaps and catching up for period 1995-2019.



As illustrated in Table I and Figure 3, Group 4 countries have the lowest 24-year average annual rate of catch-up effect, lagging furthest behind from EU-27 technology during the whole period considered.

In addition, Group 1 with the highest average annual rate of TC ratio $\left(\frac{TC_{Meta}}{TC_{Group_k}}\right)$ is the only Group in which TGR is less than unity showing that the gap is decreasing overtime while Group 3 is accelerating its catching-up speed as it is the only Group in which average annual rate of TC ratio is less than unity (Figure 3).

3.3 Second-stage regression results

Efficiency scores (TE) (Table II) and TGR values $\left(\frac{TE_{Meta}}{TE_{Group_k}}\right)$ (Table III) under VRS are treated as a dependent variable with a constrained range, while CO_2 emissions, population density, industry, population growth and urban population are treated as independent variables.

Table II. Simar-Wilson's two-sided truncated regression model for efficiency scores

Variables	Coefficient	Z	P-values	95% CI Lower bound	95% CI Upper bound
Constant	0.472715	30.55	0.000	0.4425995	0.5015383
CO_2 emissions	0.0000009	3.07	0.002	0.000000337	0.00000152
Population density	0.0004413	6.53	0.000	0.0003217	0.0005872
Industry	0.000000000002	7.42	0.000	0.000000000002	0.000000000003
Population growth	0.1205063	9.32	0.000	0.0954856	0.145866
Urban population	-0.000000011	-2.8	0.005	-0.000000019	-0.000000003

Table III. Simar-Wilson's two-sided truncated regression model for TGR values

Variables	Coefficient	Z	P-values	95% CI Lower bound	95% CI Upper bound
Constant	0.65747370	40.65	0.000	0.6249562	0.68758410
CO_2 emissions	0.00000126	3.29	0.001	0.00000049	0.00000201
Population density	0.00040990	4.78	0.000	0.0002674	0.00059480
Industry	0.000000000003	6.8	0.000	0.00000000000186	0.00000000000340
Population growth	0.09527890	7.15	0.000	0.06835550	0.12073130
Urban population	-0.0000000186	-3.95	0.000	-0.00000003	-0.00000001

Considering output oriented DEA models with the bootstrap second stage regression results provided by Tables II-III, a positive relationship in a regression model that is observed in the cases of CO_2 emissions, population density, industry and population growth indicates that, ceteris paribus, an increase in the specific variables corresponds to higher inefficiency (lower efficiency) and higher TGR (smaller technology gap between actual production technology and potential overall level), while a negative sign of estimated parameter observed in the case of urban population indicates lower inefficiency (greater efficiency) and lower TGR (larger technology gap between actual production technology and potential overall level).

4. Conclusions

Our findings show that TE when measured with respect to Group frontiers is generally higher than metafrontier TE. Furthermore, the fact that catch-up effect is less than unity for all Groups of countries, indicates that, in each case, Group total factor productivity is lagging furthest behind from EU-27 technology during the whole period considered. Additionally, we found that Group 1 with the highest levels of GDP and TC ratio, has the lowest average TGR (less than unity) showing that the gap is decreasing over time, while Group 3 is accelerating its catching-up speed as it is the only Group in which the average annual rate of TC ratio is less than unity.

Finally, the results of the second stage analysis show that an increase in CO_2 emissions, population density, industry and population growth is accompanied by a decrease in the level of efficiency and technology gap between actual production technology and potential overall level for EU-27 countries. On the contrary, an increase in level of population urbanization that reflects a critical mass of people and enabling a broader cultural range of activities and more vibrant society can support greater productivity but has a negative effect on technology diffusion as the relative influence of the state government bureaucracy on urban population mobility, leading to lower TGR.

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Appendix 1

Table 1.1 Descriptive statistics of variables used in our analysis.

Variables	Means	Standard deviation	P50	Minimum	Maximum
GDP	520000000000.00	830000000000.00	210000000000.00	5500000000.00	3900000000000.00
CO_2 emissions	120000.00	170000.00	52196.00	564.26	890000.00
Labor force	7600000.00	10000000.00	4100000.00	150000.00	44000000.00
Capital stock	3400000.00	5200000.00	1300000.00	23087.00	21000000.00
Energy use	55000000000.00	78000000000.00	25000000000.00	680000000.00	350000000000.00
Population density	169.04	243.88	107.57	16.77	1570.10
Industry	110000000000.00	180000000000.00	40000000000.00	970000000.00	1100000000000.00
Population growth	0.21	0.82	0.23	-3.85	3.93
Urban population	12000000.00	16000000.00	5300000.00	340000.00	64000000.00

Table 1.2 Countries' volume indices of GDP per capita (EU=100).

Group 1	**Group 2**	**Group 3**	**Group 4**
Country ***(Accession)***	**Country** ***(Accession)***	**Country** ***(Accession)***	**Country** ***(Accession)***
- Luxembourg *(1958)* - Ireland *(1973)*	- Denmark *(1973)* - Netherlands *(1958)* - Austria *(1995)* - Germany *(1958)* - Sweden *(1995)* - Belgium *(1958)* - Finland *(1995)* - France *(1958)*	- Malta *(2004)* - Italy *(1958)* - Czech Republic *(2004)* - Spain *(1986)* - Cyprus *(2004)* - Slovenia *(2004)* - Estonia *(2004)* - Lithuania *(2004)* - Portugal *(1986)*	- Hungary *(2004)* - Poland *(2004)* - Slovakia *(2004)* - Latvia *(2004)* - Romania *(2007)* - Greece *(1981)* - Croatia *(2013)* - Bulgaria *(2007)*
GDP per capita: More than 91.5%, above the EU average in 2018-19	**GDP per capita:** Equal or above the EU average in 2018-19, that lies between 0% and 19.5%	**GDP per capita:** Equal or below the EU average in 2018-19, that lies between -21.5% and 0%	**GDP per capita:** Below the EU average in 2018-19, that lies between - 48% and -28%