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# Information and Communication Technologies and Labor Productivity: A Dynamic Slacks-Based Data Envelopment Analysis

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## Abstract

The current paper analyzes the efficiency displayed by 24 European Union (EU) countries when fostering labor productivity and the value added via ICT investments. In particular, a dynamic slacks-based measure data envelopment analysis (SBM-DEA) model is applied to analyze the evolution of efficiency through the period 2006–2013. The ranking resulting from the SBM-DEA framework is compared with the evolution of the Digital Economy and Society Index (DESI) scores obtained by these countries. The behavior of the efficiency variables describes a group of highly ranked DESI countries exhibiting a consistent decrease in efficiency. At the same time, several lowly ranked DESI countries display efficient trends throughout the series. The results illustrate how the reliance of EU policies on the social aspects derived from the market penetration of ICTs to measure technological development contrasts with the decreasing efficiency returns derived from an increase in ICTs investment. Thus, while catching up may occur in productivity terms, divergences in technological and social developments widen as investment in ICT infrastructures continues to differ across EU countries.

**Keywords** Information and communication technologies · Labor productivity · Slacks-based measure data envelopment analysis · Efficiency · Digital economy and society index

## Introduction

The increase in the productivity of firms and growth processes of countries investing in Information and Communication Technologies (ICTs) has been consistently illustrated in the academic literature (Saba & Ngepah, 2022; Skorupinska & Torrent-Sellens, 2017). The main instruments of analysis have generally consisted of parametric regression

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methods applied to the corresponding panels of data (Dinga et al., 2023; Kaur & Kiran, 2023). Non-parametric techniques such as data envelopment analysis (DEA) remain relatively unused, with the efficiency that results from ICT investments remaining somewhat unstudied in the literature (Pieri et al., 2018). This is the case despite the analytical advantages inherent to DEA relative to standard econometric techniques. For instance, DEA is designed to consider multiple output variables simultaneously and does not require a specific functional form to formalize the technology or simplifying assumptions regarding technological change or market structure (Santos Arteaga et al., 2019; Tavana et al., 2019).

The current paper analyzes the efficiency of 24 European Union (EU) countries fostering labor productivity and the value added through their ICT investments. A dynamic slacks-based measure data envelopment analysis (SBM-DEA) model is implemented to account for the evolution and interactions across ICT investment and productivity variables through the 2006–2013 period. The ranking resulting from the efficiency analysis will be compared with the development of the corresponding countries' Digital Economy and Society Index (DESI) scores.

We follow a standard macroeconomic production approach where investment in ICT capital and infrastructures are considered inputs determining the labor productivity and value-added of countries (Ceccobelli et al., 2012; Shao & Lin, 2016). We find that investment in ICTs does not necessarily lead to higher efficiency, though it may trigger an improvement in the DESI scores obtained by a country. The analysis illustrates what may be defined as decreasing returns to ICT investment on efficiency but improvements in technological development. Countries displaying higher levels of ICT investment are neither more developed technologically—based on their DESI scores—nor more efficient in using their input resources to increase labor productivity and the corresponding value added.

The efficiency performance of ICT investments remains unrelated to its social dimension, represented by the market penetration perspective of the DESI scores. In other words, the reliance on EU policies on the social side derived from the market penetration of ICTs to measure technological development contrasts with the decreasing efficiency returns derived from an increase in ICT investments. Thus, while catching up may take place in productivity terms, divergences in technological and social developments widen as investment in ICT infrastructures continues to differ across EU countries.

The rest of the paper proceeds as follows. The next section reviews the related literature on the contribution of ICTs to economic growth and labor productivity. The "Dynamic Slacks-Based Measure Data Envelopment Analysis" section describes the SBM-DEA model. The "Variable Selection" section deals with the selection of variables and data retrieval. The "Analysis of the Results" section analyzes the results obtained. The "Alternative Scenarios" section presents alternative scenarios regarding the role played by GDP per capita and tertiary education in the analysis. The "Conclusion" section concludes and suggests future research directions.

## Literature Review

A variety of mechanisms through which investment in information and communications technologies (ICTs) enhances labor productivity and economic growth have been formally proposed. Intuitively, developing the infrastructure of the telecommunications system triggers an increase in efficiency by decreasing the costs related to information acquisition. Information efficiency is essential for investment, which, at the same time, is required to foster economic growth (Stiglitz, 2002). From a managerial perspective, an efficient implementation of ICT resources enables firm competencies and enhances its capabilities, leading to potential improvements in coordination and operation activities (Perunović et al., 2012).

### ICT Contribution to Economic Growth

Datta and Agarwal (2004) analyzed a panel of 22 Organisation for Economic Co-operation and Development (OECD) countries through the period 1980–1992, finding a positive relationship between the infrastructure of the telecommunications system and economic growth. They also observed diminishing marginal returns from investing in telecommunications for higher development levels. At the same time, Koutroumpis (2009) concluded that a critical infrastructure mass was required for ICT to foster economic growth. Specific factors such as the market penetration of personal computers, mobile phones, and the number of Internet users have also been identified as growth enhancers (Vu, 2011). Pradhan et al. (2018) recently validated that increasing ICT infrastructures fosters economic growth. Vu et al. (2020) provided a survey of the empirical analyses published between 1991 and 2018 relating ICT to economic growth. They found that, contrary to the general tendency described above, several studies described an insignificant effect of ICT on growth and concluded that the proxy variable used to account for ICT infrastructures conditioned the impact of ICT on growth.

Recent research has highlighted the importance of ICTs and the Internet as mechanisms fostering economic growth (Bilan et al., 2019; Remeikienė et al., 2021). In this regard, various factors have been considered as complements to the growth-enhancing capacity of ICT infrastructures. Nabi et al. (2022) incorporated foreign direct investment and international trade and studied the behavior of a panel of N11 countries from 2000 to 2018 via pooled mean group estimation. The authors developed an ICT expansion index that accounted for the number of fixed telephone lines, handheld wireless access, and Internet penetration. They found a significant negative relationship between ICT expansion and economic growth. Awad (2023) considered economic globalization together with ICTs and applied moments quantiles to analyze their impact using a panel of 44 sub-Saharan African countries through the 2004–2019 period. ICTs were found to have a negligible positive effect on per capita GDP growth, which decreased as per capita GDP increased.

A related line of research has highlighted the contribution of ICT capital goods to economic growth (Schreyer, 2000). Shahiduzzaman and Alam (2014) focused on the growth and productivity nexus of ICT capital in Australia throughout four decades. They found that the significant impact that IT capital had on output, labor productivity, and technical progress through the 90 s had slowed down in recent years. Laitsou et al. (2020) analyzed the effect of ICTs on growth within the Euro area from 1996 to 2016. They emphasized the importance of ICT capital for the Euro area's growth, particularly throughout the post-2008 crisis period.

We conclude by highlighting the contribution of ICTs to productivity. The literature has described the uneven effect of ICT investment depending on the level of development of the countries, with developed ones experiencing positive productivity impacts while developing countries display mixed results (Dewan & Kraemer, 2000). Dedrick et al. (2013) addressed this problem using data from 45 countries and comparing the results from 1985–1993 and 1994–2007. Upper-income developing countries obtained the most significant increments in productivity, particularly through the latter period. The authors also found that human resources and specific country features conditioned the effects of ICT on productivity.

## ICT Contribution to Labor Productivity

A substantial amount of academic literature has focused on evaluating the contribution of ICTs to labor productivity. The improvement of production processes triggered by ICTs has been identified as one of the main factors increasing labor productivity (Koutroumpis et al., 2020). Inklaar and Timmer (2008) observed that the increase in labor productivity was related to improvements in human capital and increments in the volume of ICTs. Similar results were obtained by Kallal (2015) for the Middle East and North Africa (MENA) countries where, in addition to human capital and ICTs, productivity was positively affected by education and R&D. Laddha et al. (2022) categorized a panel of 98 countries by their income through the period 2000–2015 to assess the effect that ICTs have on labor productivity. Their results highlighted the importance of telephone and broadband subscriptions as determinants of labor productivity.

In this regard, Najarzadeh et al. (2014) used data from 108 countries through the period 1995–2010 to analyze the impact of the Internet on labor productivity. In addition to the Internet, the authors found that per capita educational and health expenditures as well as physical capital positively affected labor productivity. Similarly, Hsieh and Goel (2019) illustrated the positive impact of internet usage on labor productivity growth using a sample of 28 OECD countries from 2001 to 2016.

This branch of the literature has consistently analyzed EU countries. Delays in information technology (IT) investment have been identified as one of the main causes leading to the low productivity growth in the EU (Van Ark et al., 2008). Wissner (2011) validated the positive effect of ICT on labor productivity for the German energy industry through the 1992–2005 period while noting that, despite this quality, ICT investment decreased from 2001. Relich (2017) followed a neoclassical growth accounting approach to analyze the impact of ICT on labor productivity in the EU through the 2010–2015 period. The main features improving labor productivity were e-commerce and the use of customer relationship management software. Total factor productivity—as well as labor productivity—has decreased in most EU countries over the period 2008–2018 relative to 1997–2007 (Bruno et al., 2019). In this regard, Shahnazi (2021) modified the components defining the Digital Economy and Society Index (DESI) and identified positive spatial spillover effects of ICT on labor productivity when analyzing a panel of 28 EU countries from 2007 to 2017.

Parametric regression techniques are generally applied to analyze the samples of panel data and characterize the effects described above. Relatively few articles have focused on non-parametric methods such as DEA. For instance, Kumar and Russell (2002) studied convergence processes using non-parametric methods based on DEA. As stated in the introduction, the nonparametric quality of DEA allows us to consider the effects of inputs on a set of multiple output variables while weakening requirements related to the production functions and the market structure.

Ceccobelli et al. (2012) implemented a static DEA framework to analyze the effects of ICTs on the labor productivity of several OECD countries in 1995 and 2005. These authors considered the number of hours worked, ICT and non-ICT capital stocks, value-added, and purchasing power parity as input variables. The set of countries chosen displayed declining levels of ICT capacity utilization. The analysis illustrated the general-purpose technology quality of ICTs, which require complementary investments to trigger productivity improvements (Lipsey et al., 2006; Vicente & Lopez, 2011). They also observed that differences in the accumulation of ICT capital among countries were the main factors contributing to the emergence of convergence clubs.

Shao and Lin (2016) studied the productivity growth triggered by the IT service industries of twelve OECD countries from 2000 to 2011. These authors combined the Malmquist productivity index with a stochastic production frontier approach to measure the performance of industries. They found that most of the productivity growth was caused by the technological advance of the production process enabled by IT service providers, while the change in efficiency had a discrete effect. Among the more recent research, Pieri et al. (2018) applied a frontier model to a sample of OECD countries and obtained a positive effect of ICTs on production efficiency.

## Dynamic Slacks-based Measure Data Envelopment Analysis

A dynamic SBM-DEA model is implemented to analyze the efficiency of countries enhancing the labor productivity and value added by their ICT sectors through the period 2006–2013. None of the nonparametric efficiency models described in the literature review section incorporates a dynamic evaluation technique into the analysis. This latter quality is essential to understanding the interactions of the variables across periods, a fundamental feature when considering policy implications and the design of efficient instruments to implement when managing the use of available resources.

The introduction of multiple periods within a DEA environment allows one to account for the dynamic effects derived from the planning horizon and obtain an unbiased measure of efficiency (Chen, 2009). In this regard, dynamic DEA constitutes a suitable environment where the cumulative nature of the processes determining the efficiency of decision-making units (DMUs) can be analyzed. The current framework builds on the dynamic DEA environment introduced by Tone and Tsutsui (2010), who expanded the model of Färe and Grosskopf (1996) using a slacks-based measure environment (Tone, 2001). Among the main novelties of this model, we must highlight the inclusion of carryover activities across periods through the long-term optimization setting and the use of non-radial measures, eliminating the requirement of proportional changes in the values of inputs and outputs.

The dynamic framework formalized in the current paper is described in Fig. 1. The model is composed of $n$ DMUs ($j = 1, ..., n$) with input and output values observed throughout $T$ periods ($t = 1, ..., T$). At time $t$, DMUs are endowed with a set $m$ of inputs ($i = 1, ..., m$) and carry-overs, named *links*, that are transferred across periods. Inputs are used to produce a set $s$ of outputs ($i = 1, ..., s$) per time period, while carry-overs illustrate the consequences from the production process between the current, $t$, and the next period, $t + 1$. The inputs and outputs used and produced by $DMU_j$ at time $t$ are denoted by $x_{ijt}$ ($i = 1, ..., m$) and $y_{ijt}$ ($i = 1, ..., s$), respectively.

Carry-overs constitute the main nexus across periods and define the dynamic framework of the production process among DMUs. These variables are introduced to account for the prevalence of the positive and negative consequences that result from the productive and structural capacities of DMUs.

Tone and Tsutsui (2010) classify carry-overs in four groups:

1. Desirable links, $z^{good}$, which are considered as outputs, implying that lower values relate to an inefficient behavior.
2. Undesirable links, $z^{bad}$, which are considered as inputs, implying that higher values relate to an inefficient behavior.
3. Discretionary links, $z^{free}$, that can be freely increased or decreased by the DMUs.
4. Non-discretionary links, $z^{fix}$, beyond the control of DMUs.

Carry-overs are defined in terms of time period, $t$, DMU, $j$, and item, $i$, via $z_{ijt}^{good}$ ($i = 1, ..., ngood; j = 1, ..., n; t = 1, ..., T$), with $ngood$ describing the number of good links considered.

GDP per capita and tertiary education are consequences of a given country's production process and infrastructures and could be interpreted as desirable links. However, they also constitute an input of the production process in the form of physical and human capital. Countries endowed with a higher GDP per capita and a percentage of tertiary educated workers are indeed endowed with higher inputs in their

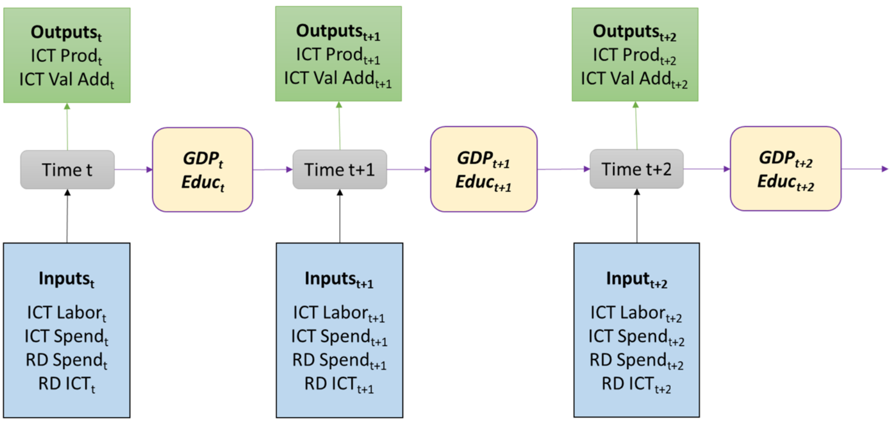



**Fig. 1** Dynamic structure of the model based on Tone and Tsutsui (2010)

production processes. This latter interpretation is more intuitive from an economic perspective and will be considered the benchmark scenario. However, several modifications of this interpretation will be analyzed throughout the paper. Note also that GDP and tertiary education are not the sole consequences of investing in ICT and R&D but constitute inputs in the production process determining the productivity and value added by the ICT sector. This is the case since they define the structural and educational constraints of the production process of each country.

Therefore, the current analysis will focus on the use of GDP and human capital by the different types of users as undesirable links $z_{ijt}^{bad}$ $(i = 1, \ldots, nbad)$. Since the main aim of the paper is to analyze the efficient use of resources in the production process, an input-oriented framework will be considered, which highlights potential decrements in the number of inputs while maintaining the observed output levels.

The set of constraints defining the evaluation problem of $DMU_o$ $(o = 1, \ldots, n)$ with undesirable links and variable returns to scale (VRS) is given by

$$x_{iot} = \sum_{j=1}^{n} \lambda_j^t x_{ijt} + s_{it}^- \quad (i = 1, \ldots, m; t = 1, \ldots, T) \tag{1}$$

$$y_{iot} = \sum_{j=1}^{n} \lambda_j^t y_{ijt} - s_{it}^+ \quad (i = 1, \ldots, s; t = 1, \ldots, T)$$

$$z_{iot}^{bad} = \sum_{j=1}^{n} \lambda_j^t z_{ijt}^{bad} + s_{it}^{bad} \quad (i = 1, \ldots, nbad; t = 1, \ldots, T)$$

$$\sum_{j=1}^{n} \lambda_j^t = 1 \quad (t = 1, \ldots, T)$$

$$\lambda_j^t \geq 0,\ s_{it}^- \geq 0,\ s_{it}^+ \geq 0,\ s_{it}^{bad} \geq 0\ (\forall i,\ t)$$

where $\lambda_j^t \in R^n$ $(t = 1, \ldots, T)$ corresponds to the intensity vector per time period, $s_{it}^-$, $s_{it}^+$, and $s_{it}^{bad}$ describe the slack variables assigned to the inputs, outputs, and undesirable links, respectively.

The consistency of the dynamic structure of the optimization problem is defined through the different carryovers across consecutive periods. The intensity vectors must be consistent across periods, allowing for the same value determined by the combination of carry-overs among firms to be defined across periods through the following conditions:

$$\sum_{j=1}^{n} \lambda_j^t z_{ijt}^{bad} = \sum_{j=1}^{n} \lambda_j^{t+1} z_{ijt}^{bad} = \quad (\forall i; t = 1, \ldots, T-1) \tag{2}$$

The corresponding input-oriented model maximizes the slacks of the inputs and undesirable links to obtain the overall efficiency of $DMU_o$ $(o = 1, ..., n)$

$$\theta_o^* = \min \quad \frac{1}{T}\sum_{t=1}^{T} w^t \left[ 1 - \frac{1}{m + nbad} \left( \sum_{i=1}^{m} \frac{w_i^- s_{it}^-}{x_{iot}} + \sum_{i=1}^{nbad} \frac{s_{it}^{bad}}{z_{iot}^{bad}} \right) \right] \tag{3}$$

subject to (1) and (2). The period and input weights, $w^t$ and $w_i^-$, are assigned exogenously to emphasize the relative importance of a particular period or input variable. The corresponding constraints should be added to the model

$$\sum_{t=1}^{T} w^t = T \ and \ \sum_{i=1}^{m} w_i^- = m \tag{4}$$

The presentation is simplified by assigning the same importance to all the periods and inputs via $w^t = 1$ $(\forall t)$ and $w_i^- = 1$ $(\forall i)$. $\theta_o^* \in [0, 1]$ represents the *overall efficiency* of $DMU_o$, namely, the weighted average of term efficiencies over the entire sample period, $\theta_o^* = \frac{1}{T}\sum_{t=1}^{T} w^t \theta_{ot}^*$. That is, the *term efficiency* of $DMU_o$ is defined as follows:

$$\theta_{ot}^* = 1 - \frac{1}{m + nbad} \left( \sum_{i=1}^{m} \frac{w_i^- s_{iot}^{-*}}{x_{iot}} + \sum_{i=1}^{nbad} \frac{s_{iot}^{bad*}}{z_{iot}^{bad}} \right), \qquad (t = 1, ..., T) \tag{5}$$

which incorporates the optimal values $\left\{ \{\boldsymbol{\lambda}^t\}, \{\mathbf{s}_t^-\}, \{\mathbf{s}_t^+\}, \{\mathbf{s}_t^{bad}\} \right\}$, derived from the minimization of (3) subject to (1) and (2).

Finally, $DMU_o$ is categorized as follows:

- *term t efficient* if $\theta_{ot}^* = 1$, i.e., $s_{iot}^{-*} = 0$ $(\forall i)$ and $s_{iot}^{bad*} = 0$ $(\forall i)$, at time $t$;
- *overall efficient* if $\theta_{ot}^* = 1$, i.e., $s_{iot}^{-*} = 0$ $(\forall i, t)$ and $s_{iot}^{bad*} = 0$ $(\forall i, t)$;
- overall efficient *iff* is term efficient for all terms.

An input-oriented SBM-DEA model will be applied to evaluate the investment efficiency of the countries categorized in the previous section. The corresponding input, carryover, and output variables are presented in Table 1.

Both constant and variable returns to scale frameworks will be studied. When assuming constant returns to scale (CRS), countries may focus on collaborating or fixing their efficiency objective on a unique target composing the frontier. This reliance

**Table 1** Input, links, and output variables

| Inputs | Intermediate variables | Outputs |
|---|---|---|
| Employment ICT sector | GDP per capita | Labor productivity ICT sector |
| Public ICT spending | | |
| Public R&D spending | Tertiary educational attainment | Value added ICT sector |
| R&D expenditure ICT sector | | |

on a particular reference as an efficiency objective differs from the constrained collaboration imposed within a VRS setting, namely, $\sum_{j=1}^{n} \lambda_j^t = 1,\ t = 1, \ldots, T$. In this latter case, countries focus on efficiency targets defined by input combinations located across the efficiency frontier. The limitations imposed by the required convex constraints on the variables composing the intensity vectors limit the capacity of the model to evaluate the countries. Eliminating the restrictions on the intensity variables while acknowledging the variability of the production sector analyzed allows for a more diverse categorization of the countries.

## Variable Selection

The selection of variables is based on standard economic principles, which are inherent to the literature analyzed in the second section and describe a direct relationship between investment in ICTs, complementary R&D activities, and labor productivity. That is, ICT and R&D investment define the inputs of the model, which, together with the level of GDP per capita and percentage of tertiary education—representing endowment links that reflect the infrastructures and human capital available to the different countries—determine the labor productivity of the ICT sector and the value it adds to the economy. The inclusion of 'public R&D spending' assumes the existence of positive spillovers—derived from the performance of R&D activities—that can be absorbed by ICTs due to their general-purpose technology quality. The availability of the corresponding data has determined the period of analysis and the set of countries chosen.

All in all, the intuition applied corresponds to standard macroeconomic growth models where the productivity of countries is determined by their investments in capital and technology together with their knowledge and income bases (López et al., 2011; Santos Arteaga et al., 2020). As highlighted in the previous section, GPD per capita could be considered as a positive intermediate link variable, namely, an output. In this regard, potential extensions of the current framework will be defined in the "Alternative Scenarios" section by modifying the role of GDP within the production structure of countries.

The majority of data has been retrieved from the Digital Scoreboard of the EU (https://digital-agenda-data.eu/). For completeness, data on tertiary education from 25 to 34 years and purchasing power adjusted GDP per capita have been retrieved from Eurostat and correspond to the series [SDG_04_20] and [SDG_10_10], respectively.

The analysis of the variables composing the Digital Scoreboard of the EU has been discontinued. Even though several variables have been added in the latter years, those allowing for an analysis of the efficiency determined by specific investment inputs and productivity outputs are available only for a limited number of years. On the plus side, the data available suffices to evaluate the evolution of most European countries. Due to data limitations, our DEA analysis covers the period 2006–2013, while the comparison with the DESI index, an average for all the years available, 2017–2022, implies a substantial temporal gap. The values of this latter variable have also been retrieved from the Digital Scoreboard of the EU.

Thus, there is a gap in your years between the end of the period defining the efficiency analysis and introducing the DESI score. This is the case even though all the variables have been retrieved from the same source. The extrapolation applied assumes that those countries improving their productivity and value-added should benefit from the corresponding structural investments through time. That is, countries with relatively large investments in ICTs will exhibit decreasing efficiency returns compensated by the structural spread of technology across their different economic actors.

Table 2 presents the main variables used to compute the DESI index. As can be observed, these variables focus on the market penetration and social and institutional aspects of ICTs, leaving aside the productivity qualities that fostered substantial investment in ICTs.

## Analysis of the Results

The efficiency results obtained from implementing the SBM-DEA model are presented in the first block of columns within Table 3 and illustrated in Fig. 2 and 3 for the CRS and VRS scenarios, respectively. These figures display the dynamic behavior of the inefficiencies exhibited by the set of countries and categorize them accordingly. In both figures, besides the fully efficient countries composing an upper-efficient group that has not been illustrated, two main groups can be intuitively observed: consistently inefficient and mildly inefficient, exhibiting wide efficiency fluctuations. As a categorization criterion, upper-inefficient countries will be defined as those behaving efficiently through several periods while remaining inefficient otherwise. Lower-inefficient countries are those behaving inefficiently throughout the whole period analyzed.

The first four countries, in terms of DESI scores, Finland, Denmark, Netherlands, and Sweden, are all inefficient. This feature is more evident within the VRS scenario, where these countries remain consistently inefficient, while some of those that were inefficient under CRS behave less inefficiently. The countries located

**Table 2** DESI components

| Dimensions | Subdimensions |
|---|---|
| Human capital | Internet user skills |
| Connectivity | Advanced skills and development |
| Integration of digital technology | Fixed broadband take-up |
| Digital public services | Fixed broadband coverage |
| | Mobile broadband |
| | Broadband price index |
| | Digital intensity |
| | Digital technologies for businesses |
| | e-Commerce |
| | e-Government |

Additional information describing DESI and its main components can be found at https://digital-decade-desi.digital-strategy.ec.europa.eu/datasets/desi-2022/indicators

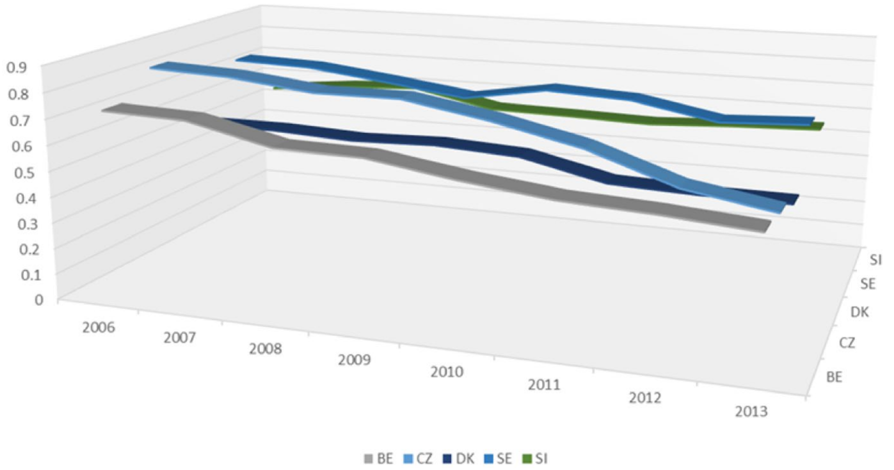
**Table 3** Efficiency scores with different model configurations

| | Benchmark | | Absent links | | Desirable links | | Links as outputs | | DESI |
|---|---|---|---|---|---|---|---|---|---|
| | VRS | CRS | VRS | CRS | VRS | CRS | VRS | CRS | |
| AT | 1 | 1 | 0.34 | 0.32 | 0.36 | 0.48 | 0.34 | 0.32 | 44.1 |
| BE | 0.65 | 0.61 | 0.43 | 0.40 | 0.44 | 0.52 | 0.43 | 0.40 | 42.5 |
| CY | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 36.0 |
| CZ | 0.95 | 0.69 | 0.55 | 0.49 | 0.68 | 0.59 | 0.56 | 0.49 | 39.2 |
| DE | 0.98 | 0.98 | 0.76 | 0.38 | 0.82 | 0.56 | 0.77 | 0.38 | 41.5 |
| DK | 0.54 | 0.48 | 0.34 | 0.32 | 0.34 | 0.45 | 0.34 | 0.32 | 56.3 |
| EE | 1 | 0.84 | 0.65 | 0.64 | 0.92 | 0.82 | 0.67 | 0.66 | 48.4 |
| EL | 1 | 0.96 | 0.87 | 0.69 | 1 | 0.82 | 0.87 | 0.69 | 28.4 |
| ES | 1 | 1 | 0.98 | 0.49 | 1 | 0.61 | 1 | 0.49 | 49.4 |
| EU | 1 | 1 | 1 | 0.46 | 1 | 0.64 | 1 | 0.46 | 41.4 |
| FI | 0.84 | 0.82 | 0.42 | 0.36 | 0.56 | 0.55 | 0.42 | 0.36 | 57.3 |
| FR | 1 | 1 | 1 | 0.50 | 1 | 0.66 | 1 | 0.50 | 41.8 |
| HU | 0.92 | 0.87 | 0.72 | 0.60 | 1 | 0.72 | 0.74 | 0.60 | 34.8 |
| IE | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 50.5 |
| IT | 1 | 1 | 0.94 | 0.50 | 1 | 0.67 | 0.94 | 0.50 | 36.6 |
| LT | 1 | 1 | 0.72 | 0.67 | 1 | 1 | 0.76 | 0.73 | 43.8 |
| LU | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 50.4 |
| LV | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 42.9 |
| NL | 0.96 | 0.94 | 0.75 | 0.47 | 0.88 | 0.62 | 0.78 | 0.47 | 54.8 |
| PT | 1 | 0.81 | 0.50 | 0.46 | 0.54 | 0.62 | 0.50 | 0.46 | 42.3 |
| RO | 1 | 1 | 1 | 0.93 | 1 | 1 | 1 | 0.93 | 24.2 |
| SE | 0.72 | 0.68 | 0.51 | 0.39 | 0.51 | 0.53 | 0.51 | 0.39 | 54.6 |
| SI | 0.88 | 0.55 | 0.41 | 0.38 | 0.47 | 0.56 | 0.41 | 0.39 | 43.1 |
| SK | 1 | 0.97 | 0.96 | 0.91 | 1 | 1 | 0.96 | 0.91 | 35.7 |
| UK | 1 | 1 | 1 | 0.53 | 1 | 0.71 | 1 | 0.53 | - |

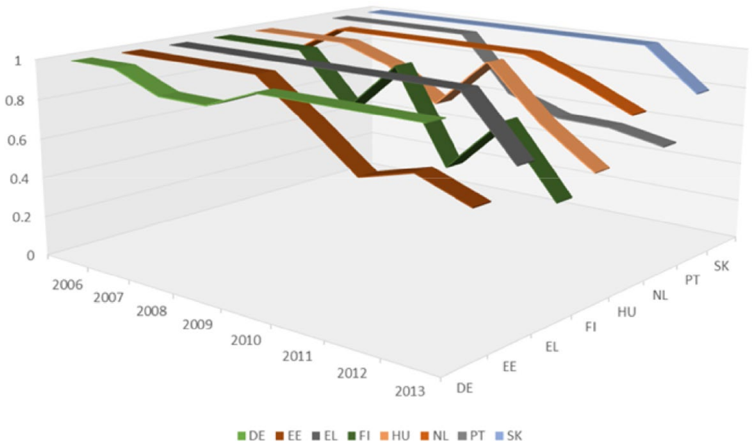
AT (Austria), BE (Belgium), CY (Cyprus), CZ (Czechia), DE (Germany), DK (Denmark), EE (Estonia), EL (Greece), ES (Spain), EU (European Union), FI (Finland), FR (France), HU (Hungary), IE (Ireland), IT (Italy), LT (Lithuania), LU (Luxembourg), LV (Latvia), NL (Netherlands), PT (Portugal), RO (Romania), SE (Sweden), SI (Slovenia), SK (Slovakia), UK (United Kingdom)

below the EU in DESI terms exhibit a variety of efficiency scores. The cases range from the efficiency of Italy, Cyprus, and Romania to the substantial inefficiency displayed by the Czech Republic, with Slovakia, Hungary, and Greece behaving more efficiently. Among the countries above the EU average DESI score, Belgium and Slovenia display inefficient behavior in both scenarios.

A potential interpretation of the result should focus on structural productivity differences across differently developed countries. As described throughout the literature review section, the accumulation of ICT developments exhibits limits among the less developed economies, while upper-developing countries can catch up to a certain extent in productivity terms. At the same time, the more developed




**(a) Lower-inefficient countries**

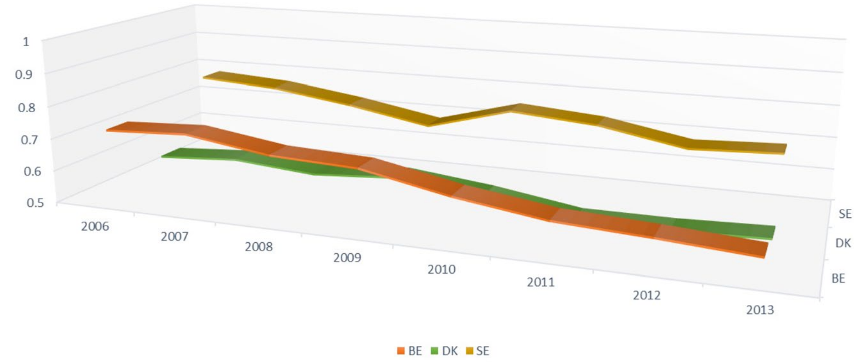



**(b) Upper-inefficient countries**

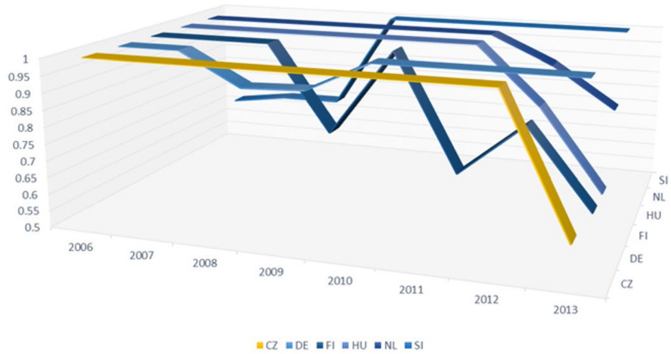
**Fig. 2** Evolution of efficiency scores with CRS

economies exhibit more structurally developed environments, though not necessarily more productively efficient.

As can be inferred from Table 3, the DESI and efficiency scores differ under both scenarios, a feature that follows intuitively from the analysis performed and the fact that SBM-DEA efficiency considers a different set of variables. DESI focuses mainly on the penetration of ICT technologies and their use across the population and economic institutions. The effects triggered by investments in ICTs on the efficiency of production processes remain outside the indicator's scope. This quality highlights the importance that the EU assigns to the different variables, leaving aside efficiency and the industrial use of ICTs—or their effect on production processes—to focus on the social aspect of the latter.




**(a) Lower-inefficient countries**




**(b) Upper-inefficient countries**

**Fig. 3** Evolution of efficiency scores with VRS

This contrast is evident in Fig. 4, where the efficiency and DESI scores are computed for the different countries. Clearly, these variables do not display a direct positive relation. Indeed, as illustrated in the first block of columns within Table 4, the Pearson correlation between the DESI and efficiency scores in both model configurations equals – 0.431 with VRS and – 0.334 with CRS. On the other hand, the correlation coefficient between the average ICT investment and the DESI score equals 0.071. This lack of a clear relationship between investment in ICTs, productivity, and the DESI score assigned to the countries is illustrated in Fig. 5.

The average ICT investment variable described in Fig. 5 is computed as follows. First, each input variable is averaged per country from 2006 to 2013. The resulting averages are then divided by the highest obtained per variable, corresponding to Germany for all inputs. Finally, the resulting normalized values of the four input variables are averaged for each country. The values obtained are those represented in Fig. 5 as "Investment ICT."

Figure 5a illustrates how countries with higher levels of ICT investment do not display higher DESI scores, a feature that applies also to their average productivity in

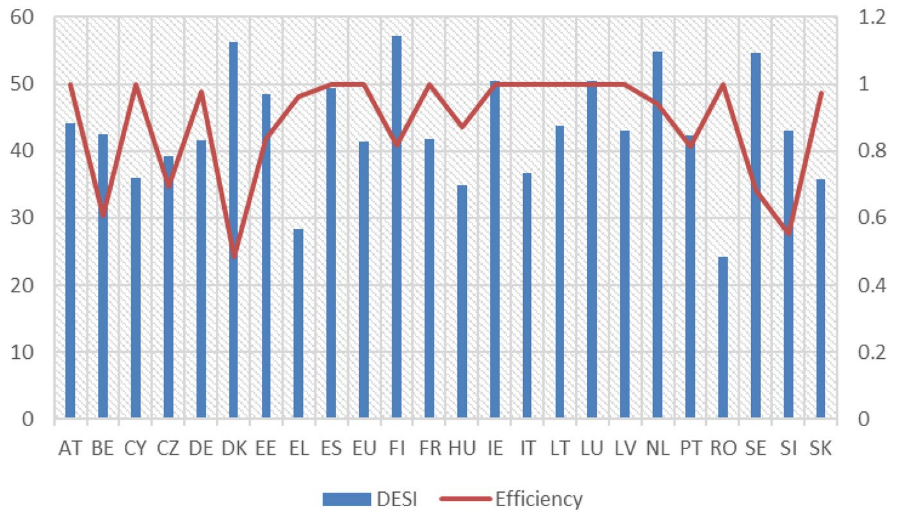


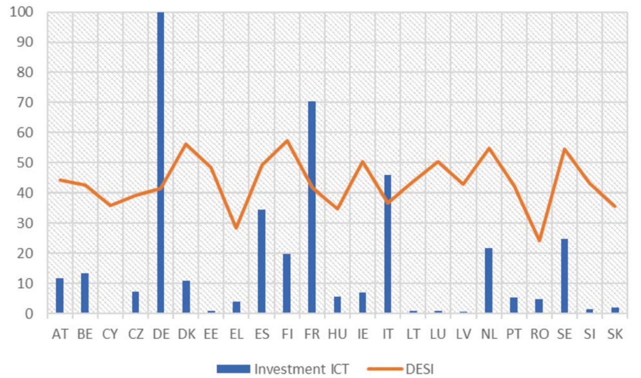

**Fig. 4** Comparing DESI with the average CRS efficiency

Fig. 5b. This latter figure illustrates how higher investments in ICTs do not necessarily increase the productivity of countries, which, as described in the literature review, is generally conditioned by the cumulative nature of infrastructures and human capital. In this regard, the correlation between ICT investment and efficiency—within a CRS setting—equals 0.181. Thus, higher investment levels do not necessarily imply higher efficiency in fostering labor productivity. Finally, as demonstrated in Fig. 5c, countries with higher productivity tend to display higher DESI scores.

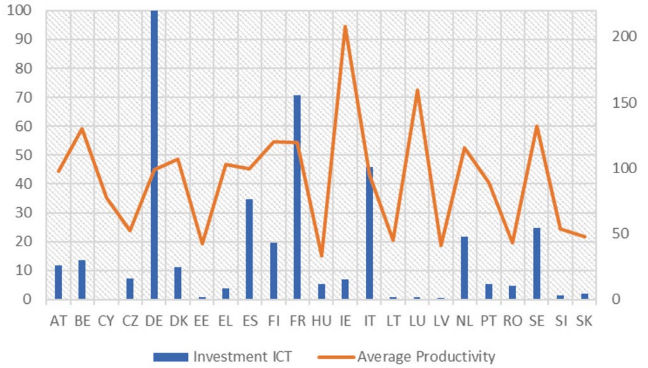
These results indicate that structural variables—including human capital—play a fundamental role in the efficiency displayed by these countries. Indeed, the correlation between GDP per capita and productivity equals 0.698, highlighting the positive relationship between both variables. A similar—though weaker—outcome and intuition arise when considering the correlation between GDP per capita and the DESI score, which equals 0.506. Analogous results are obtained when considering the correlation between tertiary education and productivity, 0.472, and tertiary education and the DESI score, 0.555. Clearly, investment alone does not determine productivity or the score of the DESI index. Thus, while more productive countries may display higher DESI scores, none of these variables significantly correlate with investment in ICTs. Therefore, the general-purpose technology quality of ICTs could be inferred from these figures, with countries requiring complementary investments to trigger improvements in productivity.

**Table 4** Efficiency and DESI correlations through the different model configurations

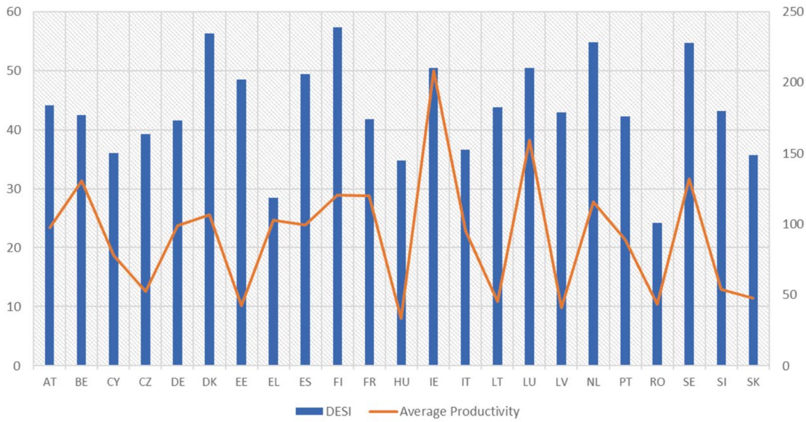
| | **Benchmark** | | **Absent links** | | **Desirable links** | | **Links as outputs** | |
|---|---|---|---|---|---|---|---|---|
| | VRS | CRS | VRS | CRS | VRS | CRS | VRS | CRS |
| Correlation | −0.431 | −0.334 | −0.399 | −0.355 | −0.412 | −0.384 | −0.388 | −0.351 |




**(a). Average ICT investment and DESI (correlation = 0.071)**




**(b). Average ICT investment and average productivity (correlation = 0.239)**




**(c). Average productivity and DESI (correlation = 0.507)**

**Fig. 5** Variable comparisons: from ICT investment to DESI development

The accumulation of ICT capital and infrastructures could foster the emergence of productivity convergence clubs. The existence of these clubs—described by Ceccobelli et al. (2012)—and the potential catching up among EU countries can be observed in Fig. 6. Consider first the countries with the highest average productivity: Ireland and Luxembourg. None of them is endowed with the highest DESI scores. Similarly, countries within the medium club displaying consistently high DESI scores, such as Denmark, Finland, Netherlands, and Sweden, are not the most productive ones, a feature also illustrated in Fig. 5c. Note how the behavior of these countries is quite heterogeneous, ranging from the fluctuations and downward tendency of Finland to the increasingly growing tendency of Sweden. Finally, among the countries displaying the lowest productivity, there are cases such as Latvia and Lithuania with relatively high DESI scores, while Romania is consistently low across both variables.

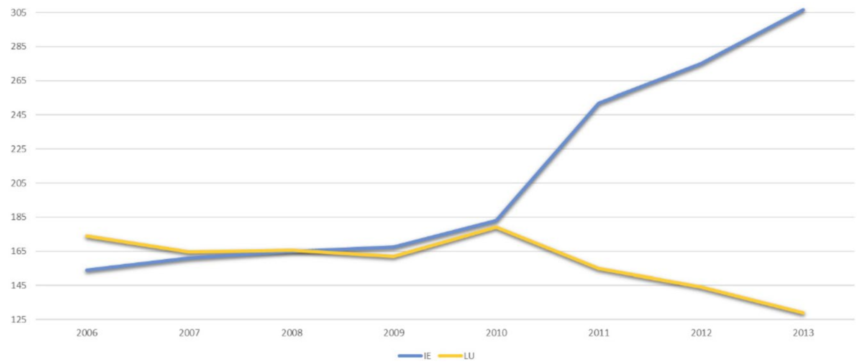
In a nutshell, the ICT investment variables can be used to describe standard income differences among countries, while links serve as structural variables conditioning the output obtained in productivity and value-added terms. In this regard, divergences in technological and social developments related to ICTs seem to be fostered by the cumulative nature of technological infrastructures and human capital.

## Validating Differences in Scores

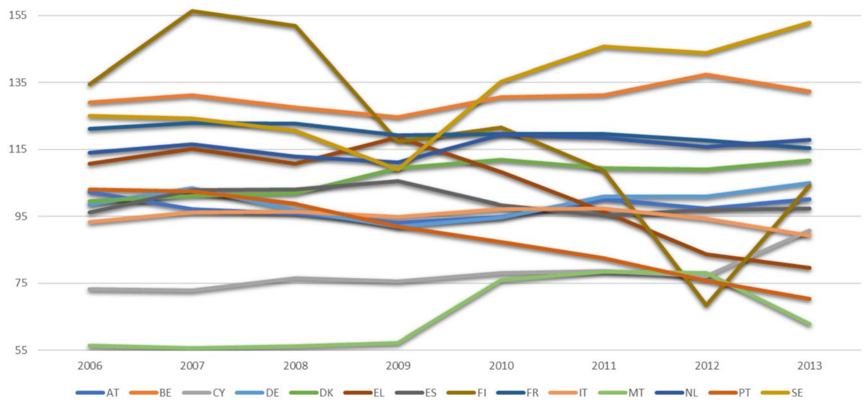
Additional intuition is provided by comparing two opposite countries in terms of the results obtained: Denmark, combining one of the top DESI scores with the lowest efficiency (Finland constitutes a similar but more moderate case), and Greece, which displays the opposite trend, namely, one of the lowest DESI indexes but a relatively high-efficiency score. The analysis aims to highlight the differences existing between industrial productive efficiency and the social evolution and development of ICTs. The EU seems to have concentrated on the latter to evaluate the behavior of countries, while the former remains a secondary objective.

The empirical literature has demonstrated that the contribution of ICTs to growth and efficiency has stalled in the latter years, with developed countries increasing their investment in ICTs that have led to lower efficiencies than those obtained by countries in their developing stages. In this regard, the comparison between Denmark and Greece should shed some light on the efficiency differences between countries and illustrate how the industrial efficiency of ICTs differs from its social penetration. Figure 7 illustrates the differences in labor productivity and added value of ICTs between Denmark and Greece. Note that right until the 2008 crisis, the Greek economy displayed a higher labor productivity, compensated by Denmark through the value added. The divergence between both series becomes evident after the crisis, with Greece falling increasingly behind Denmark in both variables.

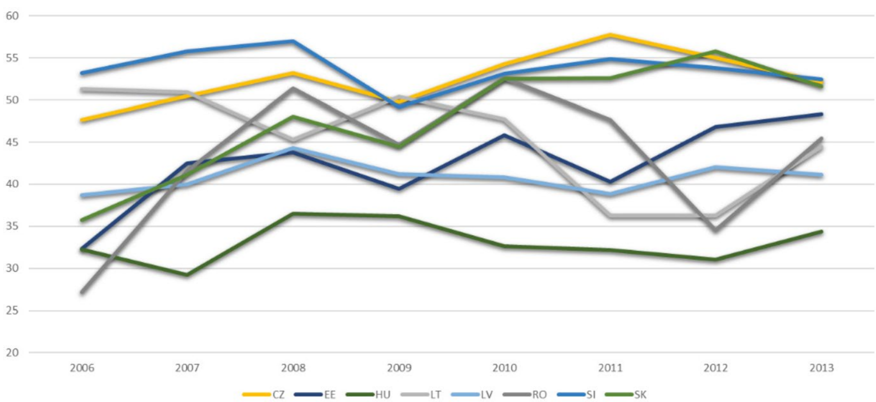
The differences between both economies regarding the two main input variables are presented in Fig. 8. The shock imposed by the 2008 crisis on the Greek economy is still evident, as is the substantial increasing divergence between R&D and ICT investments between both countries. The efficiency results obtained validate the




**(a). Highest productivity club**




**(b). Medium productivity club**




**(c). Low productivity club**

**Fig. 6** Productivity differentials across countries and convergence clubs

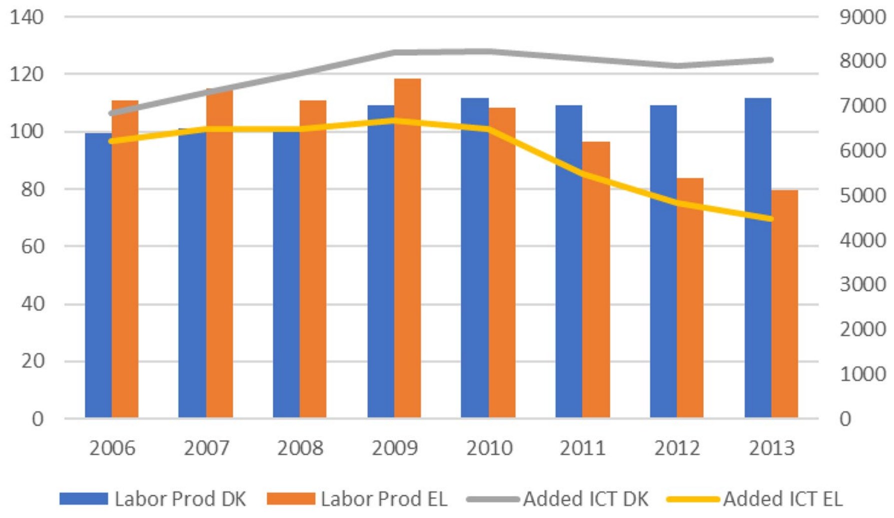



**Fig. 7** Labor productivity and added value ICT: Denmark vs. Greece

subsequent intuition and the differences in DESI scores. Productivity is not completely conditioned by investment, while these investments determine the DESI index through their cumulative effect on infrastructures and human capital, favoring a more social market penetration perspective.

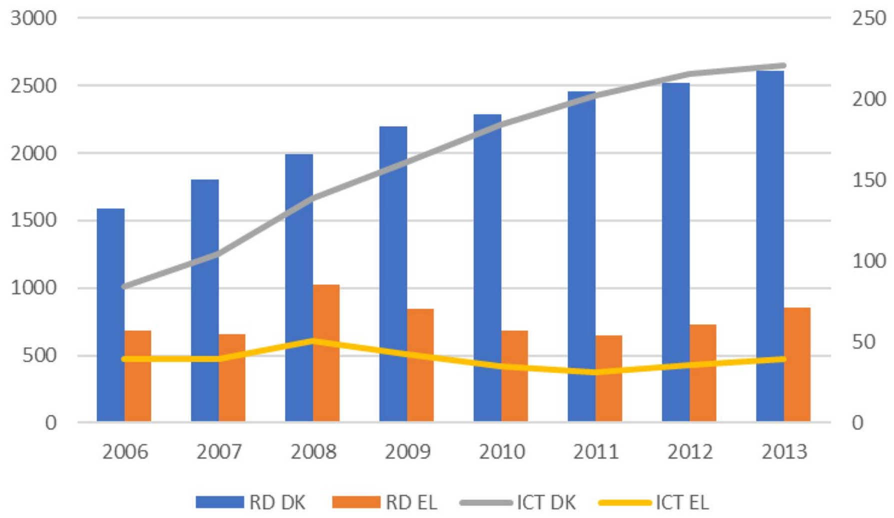



**Fig. 8** Public Expenditure differences between Denmark and Greece

## Alternative Scenarios

The results described in the previous section are conditioned by the distribution of inputs within the categories defining the SBM-DEA model. This section modifies the categorization of GDP per capita and tertiary education as undesirable links, and several alternative scenarios are defined. Three different scenarios will be analyzed. The first one eliminates the effect of GDP per capita and tertiary education as links and performs an efficiency analysis without intermediate variables. Thus, the analysis will focus on the direct relationship between employment and investment in ICTs and R&D activities and the productivity and value the ICT sector adds to the economy.

The second scenario follows a similar intuition to the benchmark but considers GDP per capita and tertiary education desirable links. The efficient use of economic resources eases the structural and educational constraints countries face. This efficiency is reflected in the performance of two of the main variables used to evaluate the economic development of countries. In this case, a higher GDP per capita and a larger percentage of the population with tertiary education constitute a positive feature and are therefore introduced as positive links. The corresponding versions of Eqs. (1) and (2) are given as

$$x_{iot} = \sum_{j=1}^{n} \lambda_j^t x_{ijt} + s_{it}^- \quad (i = 1, \ldots, m; t = 1, \ldots, T) \tag{6}$$

$$y_{iot} = \sum_{j=1}^{n} \lambda_j^t y_{ijt} - s_{it}^+ \quad (i = 1, \ldots, s; t = 1, \ldots, T)$$

$$z_{iot}^{good} = \sum_{j=1}^{n} \lambda_j^t z_{ijt}^{good} - s_{it}^{good} (i = 1, \ldots ngood; t = 1, \ldots, T)$$

$$\sum_{j=1}^{n} \lambda_j^t = 1 \quad (t = 1, \ldots, T)$$

$$\lambda_j^t \geq 0,\ s_{it}^- \geq 0,\ s_{it}^+ \geq 0,\ s_{it}^{good} \geq 0\ (\forall i,\ t),$$

and

$$\sum_{j=1}^{n} \lambda_j^t z_{ijt}^{good} = \sum_{j=1}^{n} \lambda_j^{t+1} s_{it}^{good}\ (\forall i; t = 1, \ldots, T-1), \tag{7}$$

where $s_{it}^{good}$, $i = 1, \ldots, ngood$, $t = 1, \ldots, T$, describes the slack variable assigned to the desirable links. Equations (3), (4), and (5) as well as the subsequent formal analysis remain unchanged.

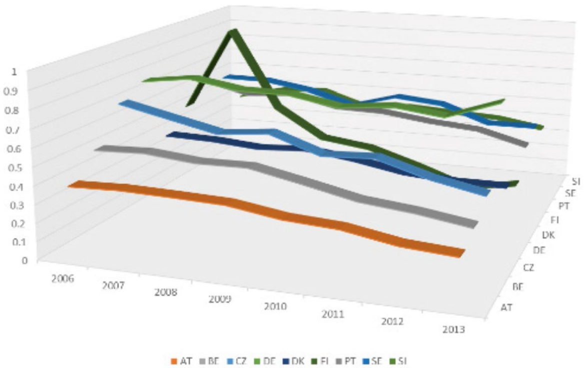
Following a similar intuition, the third scenario considers GDP per capita and tertiary education outputs from ICT and R&D processes. Desirable links behave as outputs determining the relative performance of countries through different periods but do not constitute a production objective. In this scenario, the consequences of investing in R&D and ICTs extend beyond the ICT sector and are reflected in the GDP and tertiary education of the country. That is, the importance of this sector should condition and determine the structural development of the different countries. The results obtained from these alternative scenarios are described in detail below.

The main characteristics defining the efficiency of investment in ICTs and R&D can be observed when comparing the three alternative scenarios with the benchmark. The results are described numerically in Tables 3 and 4 and illustrated graphically in Figs. 9 and 10. Note that when eliminating the links or considering them as outputs, the results obtained from the input-oriented SBM-DEA model, whose efficiency in both cases is determined by the input slacks, are almost identical. In both settings, we observe a substantial decrease in efficiency within the VRS and CRS scenarios relative to the benchmark framework. This is particularly the case when considering CRS. Only Cyprus, Ireland, Latvia, and Luxembourg remain efficient. The heterogeneous value of the DESI scores displayed by these countries provides intuition regarding the lack of correlation between the efficiencies across scenarios and the DESI index illustrated in Table 4.

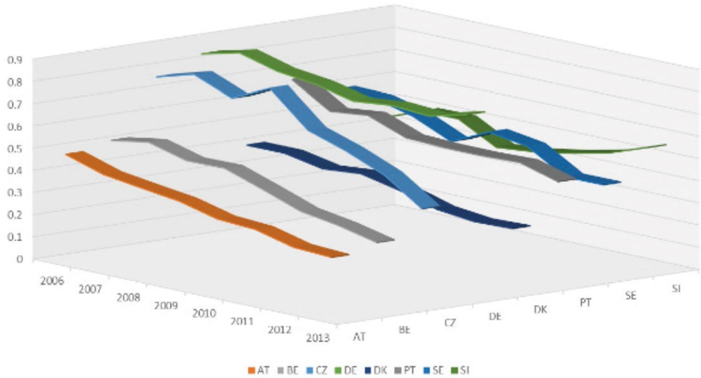
Thus, if we eliminate the cumulative importance of infrastructures from the input-oriented analysis, efficiency decreases relative to the benchmark case, where links are introduced as inputs accounting for the unequal distribution of resources among countries. A general decrease in efficiency is also observed when GDP per capita and tertiary education are introduced as desirable links representing intermediate outputs across periods. This is particularly the case with CRS, where a general efficiency loss—compensated by a small increment into full efficiency for Slovakia—can be observed. In this case, the only countries preserving an efficient profile across both scenarios and returns to scale are Cyprus, Ireland, Latvia, Lithuania, Luxembourg, and Romania. The general efficiency is, however, higher than in the previous alternative scenarios.

All in all, the literature has consistently emphasized the importance of ICT infrastructures as a positive determinant of productivity and growth. Accounting for the enhancement of ICT infrastructures leads to a general decrease in efficiency while eliminating this process or considering it as an output—within an input-oriented setting—leads to an even further decrease in efficiency. These latter analyses illustrate the raw efficiency of countries generating value and increasing productivity, which can be smoothed by introducing desirable infrastructural links and further enhanced by considering these infrastructures as inputs. We also observe how the returns from investing in ICTs in terms of efficiency are markedly lower among the most developed DESI countries.

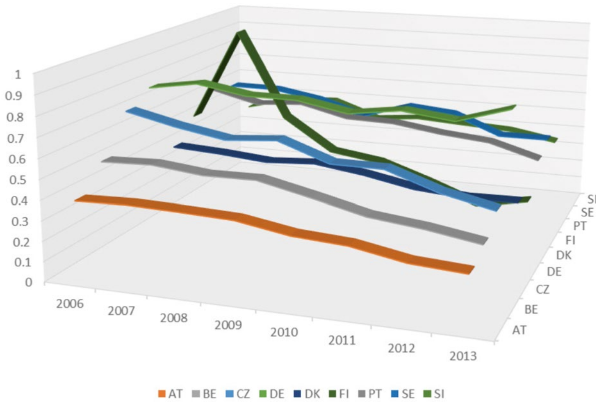
While substantial, the temporal gap between the efficiency analysis and the DESI's introduction describes the potential spillovers derived from the cumulative investment and efficient use of ICTs across countries. As illustrated in Table 4, the efficiency and DESI scores remain uncorrelated throughout all scenarios, highlighting that the enhancement of industrial efficiency differs from the market penetration process considered in DESI.




**(a). Absent links**

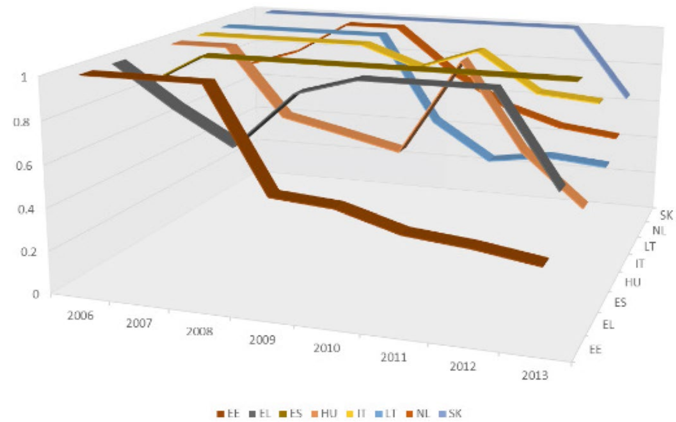



**(b). Desirable links**

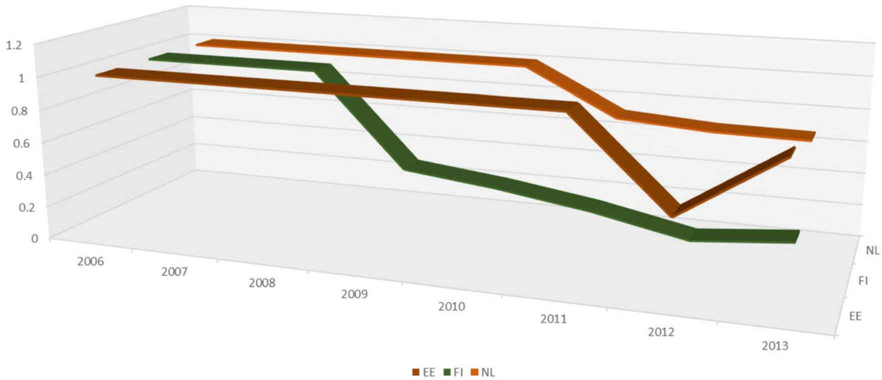



**(c). Links as outputs**

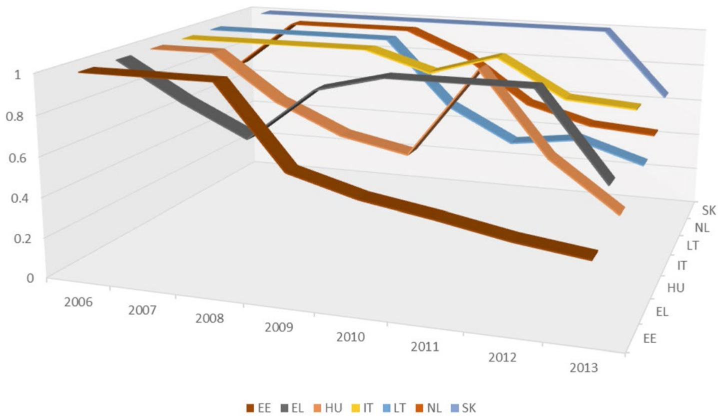
**Fig. 9** Evolution of efficiency scores with VRS: lower-inefficient countries




**(d). Absent links**

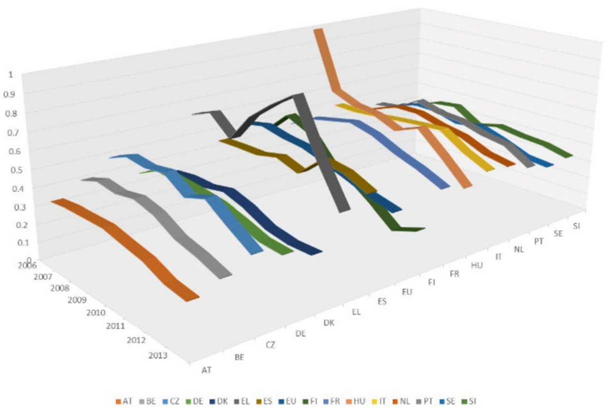



**(e). Desirable links**

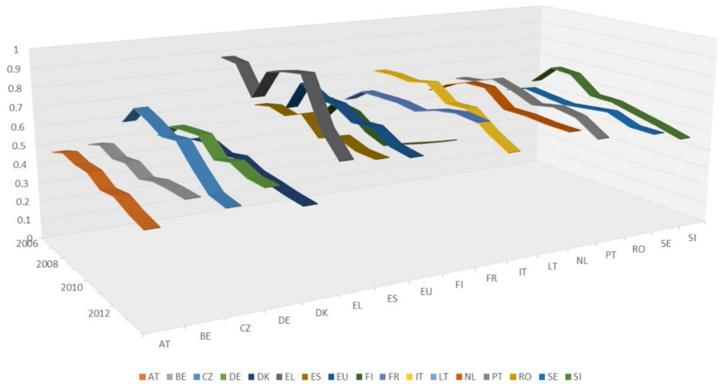



**(f). Links as outputs**

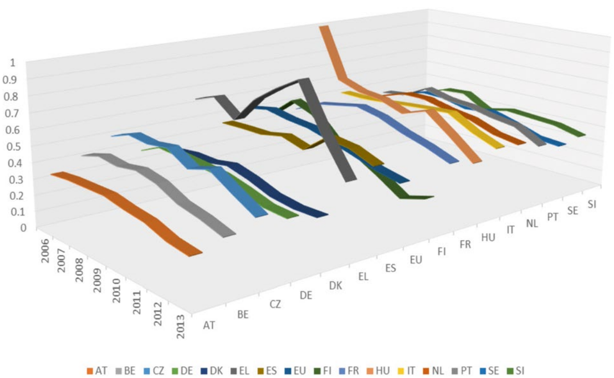
**Fig. 9** (continued)




**(a). Absent links**

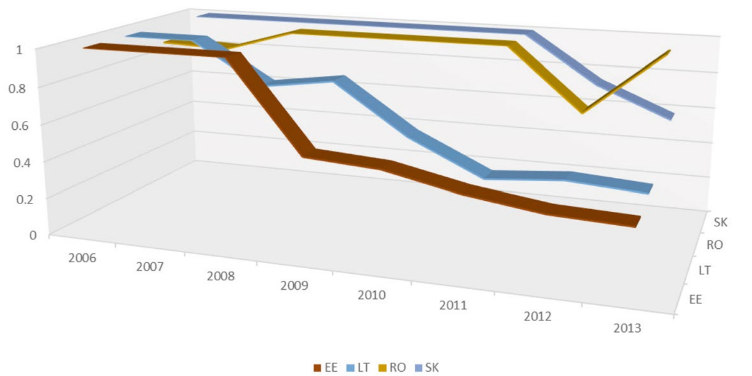



**(b). Desirable links**

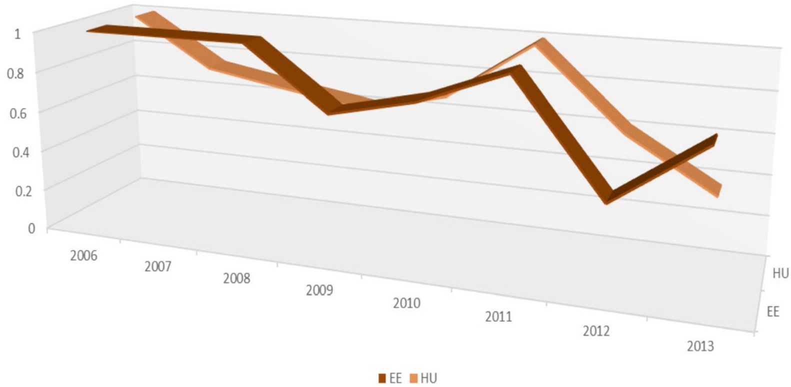



**(c). Links as outputs**

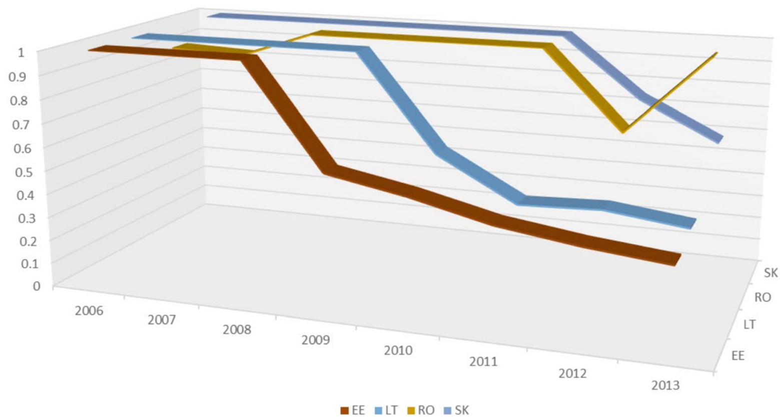
**Fig. 10** Evolution of efficiency scores with VRS: upper-inefficient countries




**(d). Absent links**




**(e). Desirable links**




**(f). Links as outputs**

**Fig. 10** (continued)

## Conclusion

The increase in labor productivity among countries investing in ITCs has been consistently illustrated in the academic literature. However, the efficiency of these investments and their effect on the technological development of countries have remained mainly unstudied. The current paper has analyzed the efficiency displayed by a set of European countries when fostering the productivity of their labor forces via ICT investments.

In particular, a dynamic SBM-DEA model has been applied to illustrate the efficiency differences in labor productivity and value-added derived from investments in ICTs across 24 EU countries. The paper has analyzed whether more efficient countries in ICT investment display a higher technological development level according to the EU DESI index.

The analysis performed confirms the decreasing productivity returns to ICT investment, with the countries displaying the highest DESI scores being all inefficient. In contrast, those with lower DESI scores, such as Cyprus, Italy, and Romania, are efficient. There are other cases ranging between both extremes. Still, the negative correlation obtained, though not significant, indicates that the efficiency performance of ICT investment does not particularly relate to its social dimension.

The results illustrate how the reliance of EU policies on the social side derived from the market penetration of ICTs to measure technological development contrasts with the decreasing efficiency returns derived from an increase in ICT investment. Thus, while catching up may occur in productivity terms, divergences in technological and social developments widen as investment in ICT infrastructures differs across EU countries.

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**Data Availability** The data used in the analyses is publicly available and the corresponding sources have been described throughout the manuscript.

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