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Measuring the Economic and Ecological Performance of OECD Countries

by

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Abstract:

The economic and ecological performance of OECD countries over two decades is measured by employing a Malmquist-Luenberger productivity index. The index credits the expansion of goods (value added) and the contraction of bads (emissions), at given inputs. We consider the inputs of capital, labor, and energy, and the emissions of CO2, So2, and NOx. The calculated indices are decomposed into measures of efficiency change ("catching up") and technical change (innovation). We analyse the variation of the results depending on the assumed returns to scale and dimensionality. Our findings suggest to employ aggregate analyses of productivity to identify crucial dimensions, which may then be analysed on a more disaggregated basis.

Keywords: Productivity; Efficiency; Environment; Dimensionality

JEL-classification: C61; O47; Q25

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1 Introduction

One of the key challenges in making the concept of "sustainability" operational is the establishment of robust quantitative methods to perform measurements of productivity and efficiency that take into account both economic and environmental dimensions. In this paper we apply methods of data envelopment analysis (DEA) to the evolution of OECD countries 1975-1990 in order to investigate to what extent the DEA-approach may contribute to tackle this challenge.

DEA is a non-parametric method to perform measurements of relative efficiency of productive units, when the comparison is difficult due to the presence of multiple inputs and outputs. Over the past two decades, it gained increasing importance and practical applicability, leading to numerous applications in a variety of fields, including the benchmarking of public utilities, private companies, or whole economies (see below). The rise of the method began when Charnes, Cooper, and Rhodes (1978) showed how to transform a fractional linear measure of efficiency into a linear programming (LP) format, thus making the computational problem relatively easily accessible to the available LP-solver software.

In essence, DEA is based on the concept of the so-called 'distance functions' in production theory (Farrell, 1957). These functions are defined in the space spanned by the considered inputs and outputs, and measure a distance between the productive unit under consideration and the production-possibility (or: best-practice) frontier. The latter is constructed as a linear combination of all productive units. Those productive units that lie on the frontier are defined to be efficient, i.e. they are attributed an efficiency score of 1.0. The other productive units are attributed an efficiency score less than 1.0, depending on their distance to the frontier. Based on this principle, many different model specifications are possible, depending on the way the efficient frontier is constructed and the distance function is defined.

For the problem at hand, i.e. efficiency measurements that include economic and ecological dimensions, we employ a relatively new class of models, namely the so-called 'directional distance functions' (Chung et al., 1997). These functions credit the expansion of goods (value added) and the contraction of bads (emissions), at given inputs. This allows to incorporate the emissions of noxious substances or greenhouse gases besides the economic output of value added and the production factors capital, labor, and energy into a production-theoretical framework. Directional distance functions relating to different points in time make up the Malmquist-Luenberger (ML) index, which measures productivity change and can be decomposed into measures of efficiency change ("catching up") and technical change (innovation). Below, we will calculate these indices for 22 OECD countries using a variety of models.

Some authors also have employed Malmquist-Luenberger productivity indices in studies that include environmentally relevant dimensions. A recent example is Färe et al. (2001) who analyze productivity growth in the manufacturing sectors of 48 US states 1947-1986 taking into account the emissions of CO, SO_2, and NO_X besides the output of value added and the traditional factor inputs of capital and labor. They assume constant returns to scale – like the study of Jeon and Sickles (2001) who investigate productivity change in selected OECD and Asian countries. The latter authors take into account the production factors capital, labor, and energy, and the emissions of CO_2. Zofio and Prieto (2001) apply similar efficiency measures, considering capital, labor, and CO_2. Obviously, such productivity and efficiency measurements raise the question of their robustness with respect to model specification, in particular the considered input and output dimensions and the assumed returns to scale.

This paper considers a variety of models to compute measures of efficiency and productivity for OECD countries, investigating their robustness depending on the model specification. We set up models that take into account the dimensions capital, labor, and energy as inputs, the emissions of CO_2, SO_2 and NO_X as undesirable output, and value added as desirable output. For each choice of dimensions we consider the cases of constant and variable returns to scale.

The paper is structured as follows. Section 2 introduces the formalism of directional distance functions, Malmquist-Luenberger productivity indices, and their decomposition into measures of efficiency change and innovation. Section 3 characterizes the employed time-series data for OECD countries. Section 4 presents the numerical results of the various models. Section 5 discusses the results and concludes.

2 Accounting for emissions in measures of efficiency and productivity

Traditional measures of productivity take into account productive inputs and the produced output, while the jointly produced emissions that potentially harm the environment are neglected. In a setting with environmental constraints or regulations, however, the regulations may induce the substitution of factor inputs, and factors may be reallocated from the production of marketable output to emission abatement activities. In other words, emission reduction is not costless. In the following we integrate this aspect of production into measures of efficiency, innovation, and productivity growth by summarizing the formalism leading to the Malmquist-Luenberger productivity index.

We denote the vector of inputs by $\vec{x} \in \mathbb{R}_+^N$, the vector of outputs by $\vec{y} \in \mathbb{R}_+^M$, and the emissions, i.e. undesirable or bad outputs by $\vec{b} \in \mathbb{R}_+^L$. The output set $P(\vec{x})$ is then defined by all the combinations of good and bad outputs $\left(\vec{y}, \vec{b}\right)$

that can be produced by the vector of inputs $\vec{x}$, i.e.

$$P(\vec{x}) = \left\{ \left(\vec{y}, \vec{b}\right) : \vec{x} \text{ can produce } \left(\vec{y}, \vec{b}\right) \right\}. \tag{1}$$

The idea that it is costly to reduce bad outputs is modeled by imposing the assumption that good and bad outputs are together *weakly disposable*[1], i.e.

$$\left(\vec{y}, \vec{b}\right) \in P(\vec{x}) \quad \text{implies} \quad \left(\lambda\vec{y}, \lambda\vec{b}\right) \in P(\vec{x}), \quad 0 \leq \lambda \leq 1. \tag{2}$$

This allows for the reduction of the bad outputs when accompanied by a simultaneous reduction of the good outputs and reflects in the simplest possible way (without explicitly modeling abatement activities) that abatement causes costs, i.e. uses resources that otherwise could have been employed to expand production.

In addition to weak disposability of good and bad output we assume that good output alone is *freely disposable*, i.e. goods may be disposed without causing costs (and without reducing bad output), i.e.

$$\left(\vec{y}, \vec{b}\right) \in P(\vec{x}) \quad \text{and} \quad \vec{\hat{y}} \leq \vec{y} \quad \text{implies} \quad \left(\vec{\hat{y}}, \vec{b}\right) \in P(\vec{x}). \tag{3}$$

Taken together, eqs. (2) and (3) reflect the asymmetry between the good (freely disposable) and bad (not freely disposable) outputs.

In view of the Laws of thermodynamics[2], which imply that any production process is coupled with the generation of emissions, we additionally impose the following assumption,

$$\text{if} \left(\vec{y}, \vec{b}\right) \in P(\vec{x}) \quad \text{and} \quad \vec{b} = 0 \quad \text{then} \quad \vec{y} = 0. \tag{4}$$

Thus, emissions are zero only if no goods are produced.[3]

For each period $t = 1...T$, the set of production possibilities $P^t(\vec{x}^t)$ that satisfies eqs. (2)–(4) can now be constructed on the basis of empirical data of inputs and good and bad outputs of the $k = 1...K$ productive units under consideration $\left(\vec{x}^{k,t}, \vec{y}^{k,t}, \vec{b}^{k,t}\right)$ by a data envelopment analysis (DEA) model:

$$
\begin{aligned}
P^t\left(\vec{x}^t\right) = \Big\{ \quad \left(\vec{y}^t, \vec{b}^t\right): \quad & \textstyle\sum_{k=1}^{K} w_k^t\, y_{k,m}^t && \geq y_m^t && m = 1...M && (5)\\
& \textstyle\sum_{k=1}^{K} w_k^t\, b_{k,l}^t && = b_l^t && l = 1...L && (6)\\
& \textstyle\sum_{k=1}^{K} w_k^t\, x_{k,n}^t && \leq x_n^t && n = 1...N && (7)\\
& w_k^t && \geq 0 && k = 1...K \quad \Big\}. && (8)
\end{aligned}
$$

Eq. (5)–(8), by which we follow Färe et al. (1994), constructs the production possibilities at time t as linear combinations of the $k = 1...K$ considered productive units, whereby the latter are weighted by the intensity variables w_k^t. The inequality constraints (5) on each of the $m = 1...M$ good outputs y_m^t imply that these are freely disposable. Together with the equality constraints (6) on each of the $l = 1...L$ bad outputs b_l^t, good and bad outputs are weakly disposable, i.e. they can be scaled down jointly to zero and therefore satisfy (2). The inequality constraints (7) on each of the $n = 1...N$ inputs x_n^t imply free disposability. The constraints (8) on the intensity variables w_k^t requires their non-negativity, which implies constant returns to scale, i.e.

$$P(\lambda\vec{x}) = \lambda P(\vec{x}), \text{ where } \lambda > 0. \tag{9}$$

In the case studies below, we will alternatively assume variable returns to scale by introducing the additional constraint

$$\sum_{k=1}^{K} w_k^t = 1. \tag{10}$$

The following two equations impose the condition of null-jointness on the good and bad outputs:

$$\sum_{k=1}^{K} b_{k,l}^t \;>\; 0 \qquad l = 1...L, \tag{11}$$

$$\sum_{l=1}^{L} b_{k,l}^t \;>\; 0 \qquad k = 1...K. \tag{12}$$

The constraints (11) state that every bad output is produced by some of the considered $k = 1...K$ productive units, (12) states that every productive unit k produces at least one of the considered $l = 1...L$ bad outputs.

In measuring efficiency and productivity we will employ the directional distance function introduced by Chung et al. (1997) which credits the contraction of bads and the expansion of goods. It is a generalization of Shepard's (1970) output distance function which seeks to increase good and bad output simultaneously. Let $\vec{g} = (\vec{g_y}, \vec{g_b})$ be a direction vector, then the directional distance function (DDF) is defined as

$$\vec{D}_0^t \left(\vec{x}^t, \vec{y}^t, \vec{b}^t; \vec{g_y}, -\vec{g_b} \right) := \sup \left\{ \beta : \left(\vec{y}^t + \beta \vec{g_y}, \vec{b}^t - \beta \vec{g_b} \right) \in P^t \left(\vec{x}^t \right) \right\}. \quad (13)$$

Here, β is the maximum feasible expansion of the good outputs $\vec{y}^t$ and proportional contraction of the bad outputs $\vec{b}^t$, at a given vector of inputs $\vec{x}^t$.

From the definition (13), it follows that the DDF is zero, if the considered vector $(\vec{y}^t, \vec{b}^t)$ lies on the production possibility frontier; we have $\vec{D}_0^t \left(\vec{x}^t, \vec{y}^t, \vec{b}^t \right) \geq 0$ for feasible vectors, and $\vec{D}_0^t \left(\vec{x}^t, \vec{y}^t, \vec{b}^t \right) \leq 0$ for infeasible vectors. Using directional distance functions with $\vec{g_y} = \vec{y}^t$, and $-\vec{g_b} = -\vec{b}^t$, the Malmquist-Luenberger (ML) index of productivity change between the periods t and $t+1$, with the technology of period t as the reference technology, is defined as

$$\mathrm{ML}^t = \frac{1 + \vec{D}_0^t \left(\vec{x}^t, \vec{y}^t, \vec{b}^t; \vec{y}^t, -\vec{b}^t \right)}{1 + \vec{D}_0^t \left(\vec{x}^{t+1}, \vec{y}^{t+1}, \vec{b}^{t+1}; \vec{y}^{t+1}, -\vec{b}^{t+1} \right)}. \quad (14)$$

Using the technology of period $t+1$ as the reference technology yields

$$\mathrm{ML}^{t+1} = \frac{1 + \vec{D}_0^{t+1} \left(\vec{x}^t, \vec{y}^t, \vec{b}^t; \vec{y}^t, -\vec{b}^t \right)}{1 + \vec{D}_0^{t+1} \left(\vec{x}^{t+1}, \vec{y}^{t+1}, \vec{b}^{t+1}; \vec{y}^{t+1}, -\vec{b}^{t+1} \right)}. \quad (15)$$

In order to avoid the use of an arbitrary benchmark technology, the geometric mean of the two indices in eqs. (14) and (15) is specified, i.e.

$$\mathrm{ML}_t^{t+1} = \left\{ \mathrm{ML}^t \times \mathrm{ML}^{t+1} \right\}^{\frac{1}{2}}. \quad (16)$$

Following Chung et al. (1997), the productivity change measured by (16) can be decomposed into measures of efficiency change ("catching up") and technical change (innovation):

$$\mathrm{ML}_t^{t+1} = \mathrm{MLEFF}_t^{t+1} \times \mathrm{MLTECH}_t^{t+1}, \tag{17}$$

where

$$\mathrm{MLEFF}_t^{t+1} = \frac{1 + \vec{D}_0^t\left(\vec{x}^t, \vec{y}^t, \vec{b}^t; \vec{y}^t, -\vec{b}^t\right)}{1 + \vec{D}_0^{t+1}\left(\vec{x}^{t+1}, \vec{y}^{t+1}, \vec{b}^{t+1}; \vec{y}^{t+1}, -\vec{b}^{t+1}\right)}, \tag{18}$$

and

$$\begin{aligned} \mathrm{MLTECH}_t^{t+1} &= \left\{ \frac{\left[1 + \vec{D}_0^{t+1}\left(\vec{x}^t, \vec{y}^t, \vec{b}^t; \vec{y}^t, -\vec{b}^t\right)\right]}{\left[1 + \vec{D}_0^t\left(\vec{x}^t, \vec{y}^t, \vec{b}^t; \vec{y}^t, -\vec{b}^t\right)\right]} \right. \\ &\times \left. \frac{\left[1 + \vec{D}_0^{t+1}\left(\vec{x}^{t+1}, \vec{y}^{t+1}, \vec{b}^{t+1}; \vec{y}^{t+1}, -\vec{b}^{t+1}\right)\right]}{\left[1 + \vec{D}_0^t\left(\vec{x}^{t+1}, \vec{y}^{t+1}, \vec{b}^{t+1}; \vec{y}^{t+1}, -\vec{b}^{t+1}\right)\right]} \right\}^{\frac{1}{2}}. \end{aligned} \tag{19}$$

Increases in productivity between t and $t+1$ are signaled by $\mathrm{ML}_t^{t+1} > 1$, decreases by $\mathrm{ML}_t^{t+1} < 1$. If there are no changes in inputs and good and bad outputs, i.e. $\vec{x}^t = \vec{x}^{t+1}$, $\vec{y}^t = \vec{y}^{t+1}$, $\vec{b}^t = \vec{b}^{t+1}$, the productivity index ML_t^{t+1} and both its efficiency change and technical change component (MLEFF_t^{t+1} and MLTECH_t^{t+1}) are unity. Of course, the components need not equal unity, if the overall productivity index does. The technical change component MLTECH_t^{t+1} measures the change of the production possibility frontier, more precisely, the change of that part of the frontier relevant for the productive unit under consideration; $\mathrm{MLTECH}_t^{t+1} = 1$ signals no change of the frontier, a change toward 'more goods and fewer bads' is signaled by $\mathrm{MLTECH}_t^{t+1} > 1$, a change toward 'less goods and more bads' by $\mathrm{MLTECH}_t^{t+1} < 1$. The efficiency change component MLEFF_t^{t+1} measures the change of the distance between the productive unit under consideration and the production possibilities frontier, whereby an increase of the distance is signaled by $\mathrm{MLEFF}_t^{t+1} < 1$, a decrease by $\mathrm{MLEFF}_t^{t+1} > 1$.

The directional distance functions $\vec{D}_0^t(t)$, $\vec{D}_0^t(t+1)$, $\vec{D}_0^{t+1}(t)$, $\vec{D}_0^{t+1}(t+1)$ can be calculated as solutions of Linear Programming (LP) problems. Let us denote the productive unit under consideration k', for the sake of illustration at $t+1$ using the technology at t as reference. Then the LP maximization problem to calculate $\vec{D}_0^t(t+1)$ for k' reads:

$$\begin{aligned}
\vec{D}_0^t\left(\vec{x}^{t+1,k'}, \vec{y}^{t+1,k'}, \vec{b}^{t+1,k'}; \vec{y}^{t+1,k'}, -\vec{b}^{t+1,k'}\right) \quad &\equiv \quad \max_{\beta, w_1^t, \ldots, w_K^t} \beta \\
s.t. \qquad \sum_{k=1}^{K} w_k^t \, y_{k,m}^t \quad &\geq \quad (1+\beta) y_{k',m}^{t+1} \qquad m = 1...M \\
\sum_{k=1}^{K} w_k^t \, b_{k,l}^t \quad &= \quad (1-\beta) b_{k',l}^{t+1} \qquad l = 1...L \\
\sum_{k=1}^{K} w_k^t \, x_{k,n}^t \quad &\leq \quad x_{k',n}^{t+1} \qquad n = 1...N \\
w_k^t \quad &\geq \quad 0 \qquad k = 1...K
\end{aligned} \tag{20}$$

Here the directional distance function $\vec{D}_0^t(t+1)$ is calculated as the maximum value of β, i.e. the maximum feasible expansion of good outputs and proportional contraction of bad outputs (at given inputs). Thus, β is both the goal function and an optimization variable in the stated LP and its constraints. The other optimization variables are the intensity variables $w_1^t, ..., w_K^t$ that weight the K productive units in the linear combination of units which make up (that part of) the efficient frontier (relevant for the productive unit k' under consideration). Note that for each productive unit k' and time interval $(t, t+1)$ four LPs have to be solved (because each unit and the reference technology can refer both to t or $t+1$). Also note that the weights $w_1, ..., w_K$ are specific for the unit under consideration. This is the reason why –somewhat intuitively speaking– the formalism can be considered as "fair" in the sense that, when evaluating the distance of a particular unit from the efficient frontier, the weights assigned to the units are chosen such that the unit under evaluation appears in the most favorable light possible.

3 Time-series data for OECD countries

In the following we calculate measures of efficiency, innovation, and productivity change for OECD countries and various models using time-series data for the productive inputs of capital, labor, and energy, the output of value added, and the emissions of CO_2, SO_2, and NO_X. The data on capital, labor, and value added is taken from the Penn World Table. The capital and output data is based on the concept of Purchasing Power Parity and given in International constant US$ of the year 1985, thus making *real* quantity comparisons possible, both between countries and over time (Summers and Heston, 1991). Total primary energy input is taken from the OECD energy balances, and the emissions data from the OECD (Environmental Data). For reasons of data availability we consider the period 1975-1990. Table 1 presents the (normalized) data of the year 1990, table 2 presents the annual average changes of these data over the considered time span.

$\longrightarrow$ InsertTables 1, 2

4 Numerical results

Using the time-series data characterized above, we calculate measures of efficiency, innovation, and productivity growth for the indicated OECD countries, based on directional distance functions as introduced in Section 2. Our aim is to systematically analyse the variation of the results depending on the model specification. We start by calculating static measures of efficiency, i.e. the directional distance function $\vec{D}_0^t(t)$ for the years $t = 1975, 1980, 1985$, and 1990. Beginning with the simplest possible model "QKL", using the output of value added and the inputs capital and labor, we successively add the input energy (model "QKLE") and the emissions of CO_2 (model "QKLEC"). For each year the efficiency index is calculated both under the assumptions of constant and variable returns to scale (Tab. 3). Furthermore, we calculate for the same set of countries and models indices that characterize the changes of the production systems over time; Tab. 4 reports the annual averages over the period 1975-1990 of the efficiency-change indices MLEFF, the technical-change indices MLTECH, and the Malmquist-Luenberger productivity-change indices ML. Again, we consider both the cases of imposing constant or variable returns to scale. Additional results for models including the emissions of SO_2 and NO_X are given in the Appendix.

⟶ Insert Tables 3, 4

5 Discussion and conclusions

Regarding the variation of the calculated efficiency measures for OECD countries depending on the model specification, one observes that the calculated indices increase systematically with the number of the considered input and output dimensions (Tab. 3). The reason is that the dimensionality of the efficient frontier increases correspondingly, i.e. more countries span this hyperplane in input-output space and thus are attributed an efficiency score of 1.0. Thus, the observation of an increase in measured efficiency due to an increase in the number of considered dimensions can be understood on the basis of the employed model structure.

Furthermore, the calculated efficiency indices increase when shifting from models with constant returns to scale (CRTS) to models with variable returns to scale (VRTS). This results from the VRTS-frontier beeing potentially more "flexible" to fit the data. Clearly, the model specification has a considerable impact on the produced quantitative results. Depending on the dimensions included and the assumed returns to scale, we find notable differences in the calculated efficiency indices (see Tab. 3).

For the considered models and countries, Tab. 4 shows the calculated annual averages (1975-1990) of the efficiency-change indices MLEFF, the technical-change indices MLTECH, and the Malmquist-Luenberger productivity-change indices ML. Whereas increases of efficiency signalled by MLEFF larger than 1.0 indicate a decreasing distance of a country from the efficient frontier over time ("catching up"), the index of technical change MLTECH reflects the shift of the frontier itself (more precisely: the shift of the relevant part of the frontier for the country under consideration). A shift in the frontier toward more output and less emissions (at constant inputs) is signalled by a value of MLTECH larger than 1.0. The presented ML-productivity indices are the product of the corresponding efficiency-change indices MLEFF and the technical-change indices MLTECH. Overall, we find that the calculated ML indices primarily reflect shifts of the frontier over time, i.e. innovation.

In the model with value added as output, capital, labor, and energy as inputs, and CO_2 emissions as undesirable output, i.e. in the five-dimensional model "QKLEC", between 7 and 10 out of the 22 considered countries lie on the frontier, if CRTS are assumed; with VRTS, between 11 and 14 countries are attributed an efficiency score of 1.0 (Tab. 3c). This confirms the general rule of thumb in operations research that the number of units to be evaluated should exceed the number of considered dimensions by at least a factor of five, if the considered units are to be well differentiated (by whatever method is used for differentiation). The results of further DEA-based models that take into account the dimensions labor and value added and subsequently add the emissions of CO_2, SO_2, and NO_X as undesirable output (see the Appendix) confirm the discussed systematic variations of the calculated indices depending on the model specification.

To compare the performance of single countries depending on model specification, we consider by way of example the efficiency indices of Germany and Sweden in 1990 (Tab. 3a-c, last column): In the case of capital and labor as inputs (model "QKL" with CRTS), the efficiency index attributed to Germany of 0.778 (ranked 14th out of 22) exceeds the one of Sweden (0.705, ranked 17th). When adding the input dimension energy, i.e. shifting to the model "QKLE", the picture changes relatively little: Germany is then attributed an efficiency of 0.878 (ranked 12th), while Sweden is attributed 0.780 (ranked 19th). If, however, CO_2 emissions are added as additional undesirable output (model "QKLEC"), the picture changes drastically: Sweden is now classified as efficient (1.000), whereas Germany is attributed an efficiency score of 0.890, falling behind on rank 18.

When interpreting the latter result, it is appropriate to take into account the composition of fuels of the two considered countries' energy consumption, in particular their electricity generation. In Sweden, electricity generation is based essentially half on hydro and half on nuclear power, both CO_2-free. In Germany, on the other hand –where comparable topographical potentials of hydro-power are not available and the contribution of nuclear power to total electricity generation is roughly 1/3–, about half of the electricity consumed is generated on the basis of carbon-intensive, indigenous lignite and (partly indigenous) hard coal, whose combustion cause considerable CO_2 emissions.

This illustrates a major challenge in evaluating aggregate measures of economic and ecological performance: The calculated results may depend sensitively on the chosen model specification, especially on the selected dimensions. Therefore, more disaggregated analyses may frequently be recommendable to investigate the composition and impact of the identified "crucial" dimensions. Besides the issue of fuel composition, as discussed, industry structure is another candidate worth of further investigation: differing capital-, labor- or energy-intensities of aggregate production may lead to measures of aggregate performance that seemingly indicate inefficiencies, while more disaggregated analyses, that take into account the different underlying industry structures, might reveal that the corresponding factor intensities rather reflect an efficient international division of labor. Of course, the argument applies in a similar way to the issue of labor qualification. In conclusion, our findings suggest to employ aggregate analyses of productivity to identify crucial dimensions, which may then be analysed on a more disaggregated basis, before drawing final conclusions on aggregate efficiency and productivity.

Notes

[1]The concept of *weak disposability* was introduced by Shepard (1970).

[2]The Laws of Thermodynamics imply that no production process can be driven without energy conversion. Energy conversion is necessarily associated with entropy production which manifests itself in the emission of heat and substances.

[3]Labeled as *null-jointness*, this assumption was introduced by Shepard and Färe (1974).

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Table 1: Normalized output of value added $q = Q/Q_0$, factor inputs of capital $k = K/K_0$, labor $l = L/L_0$, energy $e = E/E_0$, and emissions of CO_2, SO_2, and NO_X of OECD countries in 1990, in multiples of the smallest values: $Q_0 = Q(\text{IRL}) = 32.4$ Bill. Int. $\$_{1985}$, $K_0 = K(\text{IRL}) = 29.2$ Bill. Int. $\$_{1985}$, $L_0 = L(\text{IRL}) = 1.35$ Mio. employees, $E_0 = E(\text{IRL}) = 10.5$ Mtoe, $C0_2$(NOR)=28.5 Mio. t, $S0_2$(CHE)=43.0 kt, $N0_X$(IRL)=116 kt.

	q	k	l	e	CO2	SO2	NOx
AUS	7,6	10,5	6,0	8,3	9,1	n.a.	n.a.
AUT	3,0	4,3	2,7	2,5	2,0	2,1	1,7
BEL	4,1	5,2	3,1	4,6	3,7	n.a.	n.a.
CAN	14,0	19,4	9,8	20,1	14,8	76,9	18,2
CHE	3,4	8,5	2,5	2,4	1,4	**1,0**	1,4
DNK	2,2	3,2	2,1	1,7	1,7	5,0	2,4
ESP	11,5	13,2	10,5	8,7	7,4	52,7	10,1
FIN	2,2	4,0	1,9	2,8	1,9	6,0	2,6
FRA	24,3	31,7	19,3	21,7	12,8	29,1	16,3
GBR	23,4	20,6	21,0	20,4	20,1	87,5	23,7
GER	27,9	41,1	22,3	26,4	24,7	20,5	17,4
GRC	2,1	3,1	2,9	2,1	2,4	11,8	3,0
IRL	**1,0**	**1,0**	**1,0**	**1,0**	1,1	4,1	**1,0**
ITA	22,2	25,3	17,3	14,7	13,9	38,4	16,7
KOR	8,8	11,0	13,2	8,8	8,2	n.a.	n.a.
MEX	14,0	19,4	9,8	11,9	10,4	n.a.	n.a.
NLD	6,0	6,9	4,6	6,4	5,5	4,7	5,0
NOR	2,0	3,6	1,6	2,1	**1,0**	1,2	1,9
PRT	2,3	1,8	3,3	1,6	1,4	8,0	2,7
SWE	3,9	6,0	3,3	4,6	1,7	3,2	3,3
TUR	6,5	6,3	18,0	5,0	4,9	n.a.	n.a.
USA	139,5	146,2	91,3	184,0	170,0	499,6	183,3

Sources: Penn World Table, OECD Energy Balances, OECD Environmental Data
n.a.=not available

Table 2: Annual average, percentage changes of output value added, inputs of capital, labor, energy, and emissions of CO_2 (1975-1990), SO_2 and NO_X (1980-1990).

	q	k	l	e	CO2	SO2	NOX
AUS	2,9	3,8	1,9	2,4	2,4	n.a.	n.a.
AUT	2,5	4,6	0,8	1,6	0,5	-13,8	-1,7
BEL	2,3	2,7	0,6	0,9	-0,8	n.a.	n.a.
CAN	3,3	5,2	1,8	1,5	0,5	-3,3	0,7
CHE	1,9	3,1	0,6	2,2	0,6	-9,4	-0,2
DNK	2,2	2,8	0,8	0,1	-0,4	-7,1	0,3
ESP	2,5	4,8	0,9	3,0	1,8	-3,0	1,1
FIN	3,0	3,9	0,7	2,4	1,0	-7,8	0,2
FRA	2,5	3,5	0,9	2,3	-1,2	-9,4	1,4
GBR	2,5	3,0	0,5	0,4	-0,3	-2,6	1,1
GER	2,5	3,3	0,8	0,8	-0,1	-12,0	-2,6
GRC	2,5	3,2	0,7	4,1	4,6	2,4	4,7
IRL	3,8	3,8	0,8	2,8	2,6	-2,2	3,4
ITA	3,0	3,2	0,6	1,4	1,2	-7,9	1,7
KOR	8,7	9,2	2,1	8,5	7,9	n.a.	n.a.
MEX	3,3	5,2	1,8	4,7	4,8	n.a.	n.a.
NLD	2,2	3,0	1,3	0,8	0,9	-8,6	-0,1
NOR	3,2	2,7	1,3	2,3	0,9	-9,1	1,5
PRT	4,3	4,2	1,1	4,9	5,1	2,6	6,5
SWE	1,7	3,7	0,8	1,3	-3,4	-12,3	-1,4
TUR	4,2	5,4	2,1	4,6	5,5	n.a.	n.a.
USA	2,9	3,5	1,5	1,0	0,6	-0,9	-0,6

n.a.=not available

Table 3: Efficiency indices of OECD countries (directional distance functions $\vec{D}_0^t(t)$) for $t = 1975, 1980, 1985, 1990$ in the models: a) output: value added, inputs: capital and labor, b) additional input: energy, c) additionally CO_2-emissions as undesirable output. (CRTS=Constant returns to scale, VRTS=Variable returns to scale.)

a) Model QKL	1975		1980		1985		1990	
	CRTS	VRTS	CRTS	VRTS	CRTS	VRTS	CRTS	VRTS
AUS	0,840	0,919	0,838	0,902	0,833	0,879	0,787	0,849
AUT	0,805	0,872	0,732	0,846	0,591	0,782	0,627	0,791
BEL	0,788	0,940	0,857	0,978	0,764	0,887	0,841	0,964
CAN	0,908	0,945	0,897	0,931	0,915	0,939	0,930	0,958
CHE	0,887	1,000	0,927	1,000	0,868	0,974	0,879	1,000
DNK	0,575	0,816	0,524	0,780	0,608	0,842	0,574	0,760
ESP	1,000	1,000	0,882	0,893	0,740	0,760	0,813	0,821
FIN	0,470	0,805	0,545	0,810	0,575	0,780	0,656	0,882
FRA	0,803	0,808	0,818	0,831	0,752	0,764	0,789	0,805
GBR	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
GER	0,709	0,722	0,838	0,845	0,760	0,771	0,778	0,790
GRC	0,400	0,486	0,426	0,504	0,344	0,475	0,394	0,449
IRL	0,775	1,000	0,795	1,000	0,663	1,000	0,873	1,000
ITA	0,776	0,778	0,896	0,902	0,816	0,826	0,880	0,884
KOR	0,548	0,571	0,344	0,411	0,486	0,504	0,545	0,568
MEX	0,908	0,945	0,897	0,931	0,915	0,939	0,930	0,958
NLD	0,920	1,000	0,916	1,000	0,836	0,919	0,878	0,907
NOR	0,621	1,000	0,745	1,000	0,825	1,000	0,743	0,994
PRT	1,000	1,000	1,000	1,000	0,908	1,000	1,000	1,000
SWE	0,802	0,934	0,725	0,861	0,725	0,861	0,705	0,830
TUR	0,980	0,996	0,642	0,727	0,716	0,739	0,762	0,862
USA	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
mean (geom.)	0,774	0,874	0,758	0,853	0,736	0,833	0,773	0,853

b) Model QKLE	1975		1980		1985		1990	
	CRTS	VRTS	CRTS	VRTS	CRTS	VRTS	CRTS	VRTS
AUS	0,910	0,936	0,914	0,929	0,908	0,935	0,867	0,886
AUT	0,847	0,914	0,845	0,941	0,824	0,933	0,824	0,907
BEL	0,847	0,940	0,915	0,978	0,828	0,911	0,906	0,972
CAN	0,909	0,945	0,898	0,931	0,915	0,939	0,930	0,958
CHE	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
DNK	0,672	0,847	0,706	0,842	0,812	0,942	0,800	0,969
ESP	1,000	1,000	0,987	0,999	0,940	0,945	0,925	0,926
FIN	0,577	0,805	0,631	0,810	0,654	0,784	0,717	0,882
FRA	0,881	1,000	0,938	0,967	0,901	0,934	0,920	0,932
GBR	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
GER	0,795	0,923	0,915	0,945	0,845	0,897	0,878	0,919
GRC	0,788	0,847	0,772	0,842	0,639	0,777	0,565	0,644
IRL	0,776	1,000	0,837	1,000	0,761	1,000	0,874	1,000
ITA	0,843	1,000	1,000	1,000	1,000	1,000	1,000	1,000
KOR	0,548	0,576	0,382	0,572	0,649	0,728	0,636	0,707
MEX	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
NLD	0,960	1,000	0,972	1,000	0,930	0,969	0,936	0,965
NOR	0,720	1,000	0,821	1,000	0,900	1,000	0,817	0,994
PRT	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
SWE	0,864	0,944	0,822	0,888	0,805	0,883	0,780	0,848
TUR	0,980	0,999	0,840	0,934	0,865	0,947	0,865	0,966
USA	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
mean (geom.)	0,848	0,933	0,856	0,929	0,864	0,929	0,866	0,925

c) Model QKLEC	1975		1980		1985		1990	
	CRTS	VRTS	CRTS	VRTS	CRTS	VRTS	CRTS	VRTS
AUS	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
AUT	0,857	0,926	0,913	0,980	0,918	0,968	0,920	0,974
BEL	0,854	0,966	0,917	1,000	0,873	0,926	0,943	0,988
CAN	0,933	0,945	0,938	0,943	0,957	0,959	0,966	0,968
CHE	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
DNK	0,688	0,850	0,737	0,845	0,819	1,000	0,855	0,985
ESP	1,000	1,000	1,000	1,000	0,953	0,961	0,969	0,976
FIN	0,669	0,827	0,710	0,817	0,771	0,808	0,814	0,886
FRA	0,883	1,000	0,949	0,979	0,990	1,000	1,000	1,000
GBR	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
GER	0,801	1,000	0,941	1,000	0,854	0,914	0,890	0,936
GRC	0,796	0,858	0,800	0,843	0,746	0,800	0,673	0,716
IRL	0,777	1,000	0,851	1,000	0,801	1,000	1,000	1,000
ITA	0,864	1,000	1,000	1,000	1,000	1,000	1,000	1,000
KOR	0,688	0,730	0,652	0,717	0,723	0,800	0,761	0,825
MEX	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
NLD	0,973	1,000	0,983	1,000	0,960	0,991	0,957	0,985
NOR	0,852	1,000	0,937	1,000	1,000	1,000	0,956	1,000
PRT	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
SWE	0,888	0,962	0,932	0,972	1,000	1,000	1,000	1,000
TUR	0,981	1,000	0,946	1,000	0,868	0,961	0,891	0,972
USA	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
mean (geom.)	0,879	0,954	0,912	0,955	0,915	0,956	0,932	0,961

Table 4: Annual averages of efficiency change (MLEFF), technical change (MLTECH), and Malmquist-Luenberger productivity change (ML) indices of OECD countries 1975-1990 in the models: a) output: value added, inputs: capital and labor, b) additional input energy, c) additionally CO_2 as undesirable output. (CRTS=Constant returns to scale, VRTS=Variable returns to scale.)

MLEFF	a) Model QKL		b) Model QKLE		c) Model QKLEC	
	CRTS	VRTS	CRTS	VRTS	CRTS	VRTS
AUS	0,9970	0,9958	0,9974	0,9969	1,0000	1,0000
AUT	0,9908	0,9953	0,9987	0,9996	1,0037	1,0030
BEL	1,0030	1,0015	1,0035	1,0020	1,0054	1,0015
CAN	1,0014	1,0008	1,0013	1,0008	1,0021	1,0014
CHE	0,9995	1,0000	1,0000	1,0000	1,0000	1,0000
DNK	1,0000	0,9969	1,0067	1,0075	1,0091	1,0084
ESP	0,9887	0,9891	0,9952	0,9953	0,9980	0,9984
FIN	1,0086	1,0045	1,0069	1,0045	1,0078	1,0035
FRA	0,9992	0,9998	1,0024	0,9956	1,0074	1,0000
GBR	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000
GER	1,0037	1,0037	1,0048	0,9998	1,0052	0,9958
GRC	0,9998	0,9984	0,9888	0,9892	0,9935	0,9922
IRL	1,0056	1,0000	1,0056	1,0000	1,0135	1,0000
ITA	1,0059	1,0061	1,0097	1,0000	1,0086	1,0000
KOR	0,9998	0,9998	1,0042	1,0065	1,0038	1,0052
MEX	1,0014	1,0008	1,0000	1,0000	1,0000	1,0000
NLD	0,9975	0,9941	0,9985	0,9977	0,9990	0,9990
NOR	1,0062	0,9996	1,0053	0,9996	1,0063	1,0000
PRT	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000
SWE	0,9948	0,9938	0,9953	0,9942	1,0071	1,0025
TUR	0,9872	0,9917	0,9929	0,9979	0,9944	0,9982
USA	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000
mean (geom.)	0,9995	0,9987	1,0008	0,9994	1,0029	1,0004

MLTECH	a) Model QKL		b) Model QKLE		c) Model QKLEC	
	CRTS	VRTS	CRTS	VRTS	CRTS	VRTS
AUS	1,0128	1,0119	1,0104	1,0090	1,0092	1,0044
AUT	1,0041	1,0086	1,0032	1,0043	0,9996	1,0005
BEL	1,0117	1,0115	1,0107	1,0105	1,0094	1,0091
CAN	1,0108	1,0112	1,0112	1,0112	1,0092	1,0088
CHE	1,0134	1,0114	1,0055	1,0032	1,0056	1,0022
DNK	1,0052	1,0131	1,0052	1,0073	1,0009	1,0070
ESP	0,9998	0,9997	0,9963	0,9956	1,0017	1,0022
FIN	1,0134	1,0117	1,0122	1,0114	1,0042	1,0074
FRA	1,0089	1,0090	1,0058	1,0165	1,0057	1,0181
GBR	0,9999	0,9991	1,0022	1,0041	1,0103	1,0095
GER	1,0134	1,0130	1,0107	1,0174	1,0117	1,0159
GRC	1,0009	1,0010	1,0025	0,9999	1,0006	0,9986
IRL	1,0010	1,0223	1,0025	1,0201	0,9956	0,9777
ITA	1,0010	1,0015	1,0035	1,0147	1,0044	1,0043
KOR	1,0004	0,9965	0,9998	0,9942	1,0010	0,9994
MEX	1,0108	1,0112	1,0060	1,0053	1,0073	1,0103
NLD	1,0055	1,0100	1,0070	1,0076	1,0052	1,0054
NOR	1,0134	1,0138	1,0128	1,0138	1,0052	1,0045
PRT	1,0019	0,9934	0,9983	0,9700	0,9998	0,9714
SWE	1,0084	1,0111	1,0079	1,0082	1,0060	1,0067
TUR	1,0009	0,9970	0,9985	0,9978	1,0038	0,9989
USA	1,0063	1,0118	1,0068	1,0123	1,0154	1,0047
mean (geom.)	1,0065	1,0077	1,0054	1,0061	1,0051	1,0030

ML	a) Model QKL		b) Model QKLE		c) Model QKLEC	
	CRTS	VRTS	CRTS	VRTS	CRTS	VRTS
AUS	1,0097	1,0076	1,0078	1,0059	1,0092	1,0044
AUT	0,9948	1,0039	1,0019	1,0038	1,0034	1,0035
BEL	1,0148	1,0130	1,0142	1,0126	1,0148	1,0106
CAN	1,0122	1,0120	1,0125	1,0120	1,0113	1,0102
CHE	1,0129	1,0114	1,0055	1,0032	1,0056	1,0022
DNK	1,0052	1,0100	1,0120	1,0149	1,0101	1,0154
ESP	0,9884	0,9888	0,9915	0,9909	0,9997	1,0006
FIN	1,0221	1,0163	1,0192	1,0160	1,0120	1,0109
FRA	1,0081	1,0088	1,0082	1,0121	1,0131	1,0181
GBR	0,9999	0,9991	1,0022	1,0041	1,0103	1,0095
GER	1,0171	1,0167	1,0155	1,0172	1,0170	1,0117
GRC	1,0006	0,9995	0,9913	0,9892	0,9941	0,9909
IRL	1,0066	1,0223	1,0081	1,0201	1,0091	0,9777
ITA	1,0069	1,0075	1,0133	1,0147	1,0130	1,0043
KOR	1,0002	0,9963	1,0040	1,0006	1,0048	1,0046
MEX	1,0122	1,0120	1,0060	1,0053	1,0073	1,0103
NLD	1,0029	1,0040	1,0055	1,0053	1,0042	1,0045
NOR	1,0196	1,0135	1,0182	1,0135	1,0115	1,0045
PRT	1,0019	0,9934	0,9983	0,9700	0,9998	0,9714
SWE	1,0032	1,0049	1,0031	1,0023	1,0131	1,0092
TUR	0,9881	0,9887	0,9915	0,9957	0,9981	0,9971
USA	1,0063	1,0118	1,0068	1,0123	1,0154	1,0047
mean (geom.)	1,0061	1,0064	1,0062	1,0055	1,0080	1,0034

6 Appendix: Further results

Table 5: Efficiency indices of OECD countries (directional distance functions $\vec{D}_0^t(t)$) for $t = 1980, 1985, 1990$ and further models: d) output value added, input labor, undesirable output CO_2, e) additionally SO_2, f) additionally NO_X. (Constant returns to scale.)

d) Model QLC	1980	1985	1990
AUT	0,770	0,776	0,778
CAN	0,922	0,957	0,966
CHE	1,000	1,000	1,000
DNK	0,622	0,727	0,696
ESP	0,798	0,776	0,791
FIN	0,637	0,723	0,778
FRA	0,886	0,891	0,916
GBR	0,621	0,690	0,756
GER	0,885	0,853	0,868
GRC	0,709	0,622	0,539
IRL	0,573	0,555	0,619
ITA	0,895	0,892	0,918
NLD	0,955	0,903	0,899
NOR	0,874	0,959	0,904
PRT	0,943	0,903	0,815
SWE	0,810	0,874	0,982
USA	1,000	1,000	1,000
mean (geom.)	0,806	0,819	0,826

e) Model QLCS	1980	1985	1990
AUT	0,829	0,801	0,787
CAN	1,000	1,000	1,000
CHE	1,000	1,000	1,000
DNK	0,693	0,788	0,759
ESP	1,000	1,000	1,000
FIN	0,750	0,835	0,813
FRA	0,920	0,917	0,953
GBR	0,716	0,792	0,847
GER	0,891	0,869	1,000
GRC	0,766	0,731	0,639
IRL	0,636	0,599	0,687
ITA	1,000	0,948	0,940
NLD	1,000	1,000	1,000
NOR	0,897	0,987	0,916
PRT	1,000	1,000	0,965
SWE	0,876	0,930	1,000
USA	1,000	1,000	1,000
mean (geom.)	0,872	0,886	0,892

f) Model QLCSN	1980	1985	1990
AUT	0,903	0,869	0,972
CAN	1,000	1,000	1,000
CHE	1,000	1,000	1,000
DNK	0,701	0,788	0,786
ESP	1,000	1,000	1,000
FIN	0,799	0,838	0,846
FRA	1,000	1,000	0,969
GBR	0,749	0,869	0,859
GER	1,000	1,000	1,000
GRC	0,796	0,740	0,661
IRL	1,000	1,000	1,000
ITA	1,000	0,972	0,950
NLD	1,000	1,000	1,000
NOR	1,000	1,000	1,000
PRT	1,000	1,000	1,000
SWE	1,000	0,932	1,000
USA	1,000	1,000	1,000
mean (geom.)	0,932	0,938	0,938

Table 6: Annual averages of efficiency change (MLEFF), technical change (MLTECH), and Malmquist-Luenberger productivity change (ML) indices of OECD countries 1980-1990 in the models: d) output value added, input labor, undesirable output CO_2, e) additionally SO_2, f) additionally NO_X. (Constant returns to scale.)

MLEFF	d) Model QLC	e) Model QLCS	f) Model QLCSN
AUT	1,002	0,997	1,006
CAN	1,002	1,000	1,000
CHE	1,000	1,000	1,000
DNK	1,002	1,005	1,007
ESP	0,997	1,000	1,000
FIN	1,008	1,005	1,004
FRA	1,004	1,003	0,997
GBR	1,007	1,011	1,009
GER	1,004	1,010	1,000
GRC	0,989	0,990	0,989
IRL	1,003	1,004	1,000
ITA	1,009	0,994	0,995
NLD	0,996	1,000	1,000
NOR	0,828	1,002	1,000
PRT	0,991	0,997	1,000
SWE	1,006	1,012	1,000
USA	1,000	1,000	1,000
mean (geom.)	0,990	1,002	1,000

MLTECH	d) Model QLC	e) Model QLCS	f) Model QLCSN
AUT	1,008	1,024	1,011
CAN	1,012	1,026	1,033
CHE	1,009	1,011	1,021
DNK	1,010	1,005	1,003
ESP	1,006	1,020	1,011
FIN	1,009	1,003	1,006
FRA	1,012	1,006	0,995
GBR	1,010	1,004	0,993
GER	1,012	1,011	1,006
GRC	1,004	1,002	1,003
IRL	1,006	1,006	1,009
ITA	1,009	1,003	1,008
NLD	1,012	1,009	1,005
NOR	1,009	1,013	1,013
PRT	1,006	1,000	0,987
SWE	1,010	1,005	1,014
USA	1,010	1,015	1,011
mean (geom.)	1,009	1,010	1,007

ML	d) Model QLC	e) Model QLCS	f) Model QLCSN
AUT	1,011	1,021	1,017
CAN	1,015	1,026	1,033
CHE	1,009	1,011	1,021
DNK	1,012	1,010	1,009
ESP	1,003	1,020	1,011
FIN	1,017	1,008	1,010
FRA	1,016	1,009	0,992
GBR	1,017	1,015	1,003
GER	1,016	1,022	1,006
GRC	0,993	0,993	0,993
IRL	1,009	1,010	1,009
ITA	1,018	0,997	1,003
NLD	1,008	1,009	1,005
NOR	1,013	1,014	1,013
PRT	0,997	0,997	0,987
SWE	1,017	1,017	1,014
USA	1,010	1,015	1,011
mean (geom.)	1,011	1,011	1,008