Keskustelualoitteita #37
Joensuun yliopisto, Taloustieteiden laitos

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ISBN 952-458-847-1
ISSN 1795-7885
no 37

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August 2006

Abstract

This article presents a general framework for the measurement of eco-efficiency over time by generalizing the approach presented by Kuosmanen and Kortelainen (2005) from a static to a dynamic setting. For this purpose we construct an environmental performance index (EPI) by applying benefit of the doubt weighting and Malmquist index approach. Compared to other dynamic environmental productivity and efficiency analysis approaches based on these methods, our approach builds on the standard definition of eco-efficiency as it is presented in ecological economics literature. Recognizing the importance to analyze the sources of environmental performance changes, we show how the overall environmental performance index can be decomposed into two subcomponents representing changes due to technological progress (or regress) and due to changes in relative eco-efficiency. In addition, we decompose technical change into a magnitude index and a so-called environmental bias index. We apply the presented technique at the macro-level to dynamic environmental performance analysis of 21 EU countries in 1990-2000. According to the results, technical progress mostly explains overall environmental performance growth, while relative eco-efficiency changes have been minor for most countries during the sample period.

Key Words: *Benefit of the doubt weighting, Data Envelopment Analysis, Decompositions, Eco-Efficiency, Environmental productivity, Malmquist index, Technical change*

JEL classification: Q57, C43, C61, O52,

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† Financial support from the Finnish Doctoral Programme in Economics is gratefully acknowledged. An earlier version of this paper has been presented at the 4th North American Productivity Workshop, New York, USA, June 27-30, 2006, and at the 2nd International Conference on Quantified Eco-Efficiency Analysis for Sustainability, Egmond aan Zee, Netherlands, June 29-30, 2006. I would like to thank the participants of these events, and Timo Kuosmanen and Mika Linden for valuable comments and suggestions.

1. Introduction

Eco-efficiency of production concerns the capability to produce goods and services by polluting the environment and using natural resources as little as possible. In ecological economics literature eco-efficiency is commonly defined as a ratio of economic value added to environmental damage added (see e.g. Schmidheiny and Zorraquin,1996; Schaltegger and Burrit, 2000; Figge and Hahn, 2004). The challenge in the measurement of eco-efficiency is to aggregate various environmental pressures related to the emission of harmful substances and depletion of natural resources into a single environmental damage index. Most eco-efficiency measures or indicators presented in the literature are either very limited or depend on some subjective arbitrary aggregation weights. In a recent paper Kuosmanen and Kortelainen (2005) presented a more general approach for eco-efficiency measurement, which does not demand subjective aggregation weights or experts' opinions and accounts for various substitution possibilities between different natural resources and emissions. For constructing the eco-efficiency measure, they use the so-called *benefit of the doubt weighting* scheme based on *Data Envelopment Analysis* (DEA) method (Farrell, 1957; Charnes, Cooper and Rhodes, 1978) that is an extensively used non-parametric linear programming method for evaluating performance of comparable production units such as firms or non-profit organisations.

As the approach presented by Kuosmanen and Kortelainen (2005) cannot account for technical change or explain changes in environmental performance over time, it can be primarily used for eco-efficiency analysis only in a static framework. The aim of this article is to present a general framework for the measurement of eco-efficiency over time by generalizing the method presented by Kuosmanen and Kortelainen (2005) from a static to a dynamic setting. For this purpose we utilize the Malmquist productivity index that was introduced as a theoretical index by Caves et al. (1982) and developed and popularized as an empirical index by Färe et al. (1994a, 1994b). By using benefit of the doubt weighting that is a dual to Shepard's (1953, 1970) distance function approach, we construct an *environmental performance index* (EPI) that allows dynamic eco-efficiency analysis. Compared to other dynamic methods of productivity and efficiency analysis, our approach builds both on environmental impact assessment and the standard definition of eco-efficiency presented in ecological economics literature. Due to the chosen framework, we focus explicitly on the tradeoffs between the creation of economic value added and its undesirable side-effects to the environment, without direct recourse to physical inputs and outputs. Related to this orientation, we also approach environmental performance assessment from a more aggregated perspective than is typically done in productivity and efficiency analysis literature.

In the case of dynamic analysis, it is also important to analyze the sources of changes in environmental performance over time. Following Nishimizu and Page (1982) and Färe et al. (1994b), we show how the overall environmental performance index can be decomposed into two sub-components representing the changes due to technical progress (or regress) and due to changes in relative eco-efficiency. Further, by applying the decomposition of Färe et al. (1997), we show that the technical progress component can be expressed as a product of a magnitude change index and a so-called emission bias index. The latter index reveals us important information, because it recognizes the possible bias in productivity of different environmental pressures. Although the presented decomposition of the environmental performance index is comprehensive, it does not demand price information for emissions or environmental pressures in any stage.

The proposed approach is applied to dynamic environmental performance analysis of 21 EU25 countries in 1990-2000. We account for various different air pollutants and real gross domestic product (GDP) for each country. The purpose of the application is to examine how changes of environmental performance and its components have developed during the sample period in general and identify major factors in each country's performance growth. We believe that the application illustrates the possibilities and advantages of the presented methodology.

The rest of the paper is organized as follows. In Section 2 we present some important concepts and discuss eco-efficiency measurement in a static framework. Section 3 outlines our methodology for dynamic eco-efficiency analysis by presenting environmental performance index and its decomposition. Then in Section 4, we use the proposed method for analyzing environmental performance of 21 EU countries during 1990-2000. Lastly, Section 5 presents some concluding remarks.

2. Background

2.1. Environmental pressures and value added

In this section we first discuss concepts related to eco-efficiency measurement on a general level and then present the framework for eco-efficiency measurement in a cross-sectional setting. As in Kuosmanen and Kortelainen (2005), we base our approach to the definition of eco-efficiency as a ratio of economic value added to environmental damage or pressure index, approaching environmental performance measurement from a social point of view. Since our approach is essentially based on this definition, it is important to consider in more detail what is actually meant by the numerator and denominator of eco-efficiency ratio.

In this paper we use the notion of “environmental pressure” to refer to an environmental theme or category that is influenced by multiple pollutants contributing to the same environmental problem. One typical example of an environmental pressure category is global warming potential (GWP) that is affected by carbon-dioxide (CO_2), methane (CH_4) and other green house gases. We can translate the amounts of different green house gases into a single environmental pressure category measured in carbon-dioxide equivalents by using scientifically valid global warming potential (GWP) multipliers (see Houghton et al., 1996). Besides green house gases, scientifically sound conversion factors based on environmental impact assessment often enables us to aggregate other emissions into broader environmental pressure categories. For example, nitrogen oxide and sulphur dioxide emissions can be translated into acid equivalents and thus aggregated into a single acidification potential category. Although a single environmental pressure is usually related to only one environmental problem in contrast to an individual pollutant that can affect many environmental problems, environmental pressure is not yet an adequate measure for the true environmental impact. In fact, the relationship between the environmental pressure and the ultimate environmental impact can be complex, nonlinear, and very difficult to predict. Still, we think that it is more justified to base eco-efficiency measurement on environmental pressures than individual emissions such as CO_2 or SO_2, because environmental pressures account for information about relative harmfulness of certain individual pollutants. In addition, environmental pressure categories indeed represent environmental problems which we are ultimately interested in, not just amounts of emissions. For a more detailed discussion about environmental pressures and aggregation possibilities of individual pollutants we refer to Kuosmanen and Kortelainen (2005).

Another important concept to be considered is economic value added, which is the numerator of the eco-efficiency ratio. We assume throughout the text that it is possible to measure or calculate value added for all evaluated units. This is a meaningful assumption at the macro level, because we can use gross domestic product (GDP) at a national level (or gross regional product (GRP) in regional level) as a measure for economic value added. Note that as GDP does not include intermediate outputs, it measures the value added of an economy, not gross output.[1] Thus, it is justified to use GDP in a cross-country eco-efficiency analysis, as we do in the empirical application. In the same way, one can use GDP by industry at the industry level analysis; in that case GDP represents the value that the industry adds to the production process.

At the firm level, economic value added can be defined as the total revenue minus the cost of intermediate inputs. Thus, economic value added is basically the same as the sum of firm's profit and its labour and capital costs. This definition results from the society's point of view: wages and rents represent income for society, not expenditure. Although value added has an intuitive meaning also at the firm level, in practice we may not have such data available or alternatively value added cannot be calculated because of the unreliability of price data. Another more problematic situation arises for public sector firms and non-profit organizations, where either prices do not exist or where existing prices have little economic meaning, as in the case of subsidised health or education services. In these kinds of circumstances, one either has to use proxy variable or alternatively aggregate different outputs and inputs in some way to get a single value added measure. One possibility is to apply DEA-based weighting to both environmental pressures in the denominator and the economic outputs and inputs in the numerator of the eco-efficiency measure (see Kuosmanen and Kortelainen, 2005). Thus, it is worth emphasizing that despite some data problems eco-efficiency analysis is generally possible at the micro level as well, although eco-efficiency may typically have more universal content at a more aggregated level. Instead at the micro level, what specifically constitutes eco-efficiency commonly depends on the specific production processes, and thus, on the industry the evaluated firms or other units belong to.

Related to the concepts and variables used, one should note that value added includes either explicitly or implicitly the impacts of such emissions that have a direct effect on economic activity. This implies that certain micro-level environmental externalities are fully internalized as social costs in value added. However, many environmental pressures are not fully or even partially internalized, because they do not have a direct effect on economic activity. Therefore, it is reasonable to account for physical environmental indicators separately from value added, as is done in eco-efficiency analysis.

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[1] The difference between gross output and value added is important in traditional productivity measurement studies, because both have been used as output. Due to data availability, value added (or GDP) has been utilized more commonly (see OECD, 2001).

2.2. Cross-sectional setting

In this section we discuss how eco-efficiency can be measured in a cross-sectional setting using the so-called *benefit of the doubt weighting* scheme based on Data Envelopment Analysis (DEA: Farrell, 1957; Charnes, Cooper and Rhodes, 1978).[2] In contrast to other environmental performance techniques applying DEA and activity analysis, our approach is consistent with the definition of eco-efficiency given in ecological economics literature and does not consider explicitly physical inputs and outputs of the production process.[3] Instead of non-parametric environmental performance studies, our approach is closer to studies that use DEA-based weighting method but do not consider phycical inputs and outputs (compare e.g. Cherchye, 2001; Cherchye et al., 2004; Cherchye and Kuosmanen, 2006, Cherchye et al., 2006).

Suppose now that there are N comparable production units or activities (e.g. regions, countries, firms etc.) to be evaluated. Let V_k denote the economic value added and $\mathbf{Z}_k$ vector of environmental pressures generated by the production unit k. Now using this notation, we can define eco-efficiency formally as a ratio of economic value-added to the environmental damage index

$$EP_k = \frac{V_k}{D(\mathbf{Z}_k)}, \tag{1}$$

where D is the unknown damage function that aggregates M environmental pressures into a single environmental damage score.[4] Note that (1) is an ‘absolute’ measure in the sense that it does not reveal any baseline to which to compare the given eco-efficiency value. Thus, to separate (1) from relative eco-efficiency, we call it *environmental performance measure* and denote it by EP_k. In addition to eco-efficiency, some authors use the notion of *environmental productivity* for a pure ratio of value added and environmental damage index.[5] This is perhaps a more informative term, because (1) resembles more traditional partial productivity measures such as labour productivity

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[2] For a more detailed presentation about eco-efficiency measurement in a static setting, see Kortelainen and Kuosmanen (2004) and Kuosmanen and Kortelainen (2005).

[3] For different environmental performance measurement techniques based on DEA, see e.g. Tyteca (1996) and Kuosmanen and Kortelainen (2004).

[4] For the definition of eco-efficiency as a ratio of value added to environmental damage index, see e.g. Schaltegger and Sturm (1990), Schmidheiny and Zorraquin (1996), Schaltegger and Burrit (2000), Helminen (2000), Figge and Hahn (2004).

[5] See e.g. Repetto (1990), Pearce (2001), Huppes and Ishikawa (2005).

than efficiency measures.[6] However, as the notion of environmental productivity is also used in the context of total factor productivity measurement in a different meaning, for clarity, we use here the term environmental performance measure when referring to the eco-efficiency ratio in (1).[7]

Note that the pure value of EP_k is not very informative as such: if the value is 2.38, how should we interpret that? Indeed, we are usually interested in comparing production unit's eco-efficiency value with the values of other comparable units that face same kinds of environmental challenges. For example, at the intra-industry level such as energy, environmental performance of certain heavily polluting firms can be moderate or good relative to their competitors, although it would be weak compared to typical firms in less-polluting industries. Therefore, to get insight of the relative performance of the evaluated unit *k*, we have to compare it with the best performers of the sector or group. To this end, we introduce the notion of *relative eco-efficiency* as the ratio of environmental performance measure (1) to the maximum observed environmental performance in the sample, formally defined as

$$(2) \qquad EE_k \equiv \frac{EP_k}{\max\limits_{n \in \{1,\ldots,N\}} EP_n}.$$

Now, to solve relative eco-efficiency scores, we have to use some weighting method for constructing environmental damage score $D(\mathbf{Z}_k)$. For that purpose, we take a weighted sum $D(\mathbf{Z}_k) = \sum_{m=1}^{M} w_m Z_m$ of various environmental pressures and apply the *benefit of the doubt* weighting scheme. This approach does not assume any *a priori* chosen weights for different environmental pressures, but applies the most favorable weights that maximize the relative eco-efficiency of the evaluated unit in comparison with the maximum attainable eco-efficiency. Formally, the relative eco-efficiency for unit *k* can be calculated as

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[6] Value added per unit of environmental pressure definition of environmental productivity is analogous to value added per hour worked definition of labour productivity (see e.g. Repetto, 1990).

[7] Some studies use the notion of environmental productivity index when referring to the ratio of environmental sensitive total factor productivity index to the traditional total factor productivity index; see e.g. Chapple and Harris (2003), Ball et al. (2004), Managi et al. (2005) and Managi (2006).

$$
\begin{aligned}
& EE_k = \max_{\mathbf{w}} \frac{V_k}{\sum_{m=1}^{M} w_m Z_{km}} \\
& s.t. \ \frac{V_k}{\sum_{m=1}^{M} w_m Z_{nm}} \leq 1 \qquad \forall n = 1,\ldots,N \qquad \text{(normalization constraint)} \\
& w_m \geq 0 \qquad\qquad\qquad \forall m = 1,\ldots,M \qquad \text{(non-negativity constraint).}
\end{aligned}
\tag{3}
$$

In other words, we employ weights w_m ($m = 1,\ldots, M$) that maximize the eco-efficiency ratio, subject to the normalization constraint that the highest attainable efficiency score does not exceed the maximum index value of one when the same weights are applied across all sample units. Since non-negativity constraint guarantees that individual weights cannot be negative, eco-efficiency scores for all units lie within the interval [0, 1]. The evaluated production unit will be considered as eco-efficient, if its eco-efficiency score EE_k is equal to one; otherwise it will be regarded as inefficient.

Although problem (3) is intuitive and has a direct link to the ratio-definition of eco-efficiency, it is a fractional linear programming problem involving a non-linear objective function and non-linear constraints, which makes it computationally demanding. However, the problem is easy to linearize by solving the reciprocal problem

$$
\begin{aligned}
& \left(EE_k\right)^{-1} = \min_{\mathbf{w}} \left\{ w_1 \frac{Z_{k1}}{V_k} + w_2 \frac{Z_{k2}}{V_k} + \ldots + w_M \frac{Z_{kM}}{V_k} \right\} \\
& s.t. \\
& w_1 \frac{Z_{n1}}{V_1} + w_2 \frac{Z_{n2}}{V_1} + \ldots + w_M \frac{Z_{nM}}{V_1} \geq 1, \quad \forall n = 1,\ldots,N \quad \text{(normalization constraint)} \\
& w_m \geq 0 \qquad\qquad\qquad\qquad\qquad \forall m = 1,\ldots,M \quad \text{(non-negativity constraint).}
\end{aligned}
\tag{4}
$$

This problem is linear in terms of the unknown weights w_m and can be solved by standard linear programming algorithms. The relative eco-efficiency score is obtained by taking the inverse of the optimal solution to (4). Importantly, the measurement units of value added and environmental pressures do not have an effect on the value of relative eco-efficiency, because the eco-efficiency measure is units invariant. As noted in Ebert and Welsch (2004), the units invariance is a desirable property that any meaningful environmental index should satisfy, but still many indices or indicators suggested in literature do not satisfy it.

An important property of the benefit of the doubt weighting scheme is that it does not demand any prior information concerning weights of different environmental pressures; the only constraint for weights in (4) is their non-negativity. Interestingly, while any normative judgement is not required, such information can be included straightforwardly by using relative weight constraints.[8] Generally, weight constraints enable us to include stated preference information into this objective assessment. One could, for example, use contingent valuation to determine a distribution of subjective weights among individuals, and restrict weights to lie within a certain confidence interval (e.g., 95% or 99%) obtained from the subjective valuations. Another possibility would be to use stated opinions of an expert panel, as in Cherchye et al. (2006). It should be noted that weight constraints can be utilized in both cross-sectional and panel data settings.

For the purpose of dynamic eco-efficiency analysis, it is also important to note that the presented benefit of the doubt weighting approach is equivalent (i.e. dual) to the Shephard's (1953, 1970) distance function approach employed in the literature of productive efficiency analysis.[9] This equivalence between methods results from the duality of linear programming and is relatively easy to prove. In the present context, the duality property implies that Shepard's input distance function gives exactly the same results as the weighting approach and can thus be equally well used for eco-efficiency analysis. In contrast to the weighting approach, input distance function does not have a direct link to the eco-efficiency ratio, but has a more intuitive geometrical interpretation. Indeed, input distance function measures production unit's radial distance to the efficient frontier which consists of efficient or best-practice units, i.e. units with eco-efficiency score equal to one. In the present context, this distance indicates the maximum equiproportionate reduction potential in all environmental pressures that is technically possible at the present level of economic value added. Although the weighting approach does not have this same geometrical interpretation, it also estimates the same efficient frontier and eco-efficiency scores.[10] Therefore, as it is always possible to calculate eco-efficiency scores using benefit of doubt weighting (i.e. formula (4)) instead of input distance function, we use the former due to its straight and intuitive connection to eco-efficiency ratio (1).

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[8] For weight constraints in DEA, see e.g. Allen and Thanassoulis (1997) and Pedraja-Chaparro et al. (1997), for review.

[9] The distance function can be used as a generalized representation of production technology, as a measure of the technical efficiency of a firm, as well as a basis for the measurement of total factor productivity (see, e.g. Färe and Primont, 1995; Russell, 1999).

[10] For graphical illustrations of the weighting and distance function approach, see Kortelainen and Kuosmanen (2004).

3. Dynamic eco-efficiency analysis

3.1. Links to literature

In the previous section we presented how to measure eco-efficiency in a static or cross-sectional setting. Now suppose we observe the sample of production units over several time periods. We can use the above presented method in the case of panel data as well. Perhaps the most simple way is to forget different time periods altogether by pooling observations of different periods together and then estimating a common efficient frontier and eco-efficiency scores using weighting approach presented in (4). Another possible alternative is to estimate efficient frontier for each time period separately by using only observations of the same period. In this case relative eco-efficiency value of production unit *k* observed in period *s* is calculated relative to the frontier of period *s*. As presented, both approaches can be applied quite straightforwardly. However, a common limitation for these approaches is that they do not account for technical progress (or change) which may in practice have a substantial effect on the environmental performance in the long run. A second important limitation of these approaches is that they cannot explain observed changes in environmental performance over time. Therefore, our purpose is to present a general framework for dynamic eco-efficiency analysis that allows technical progress and can also explain sources of environmental performance changes.

The presented dynamic approach is based on the ideas of total factor productivity measurement literature and, in particular, Malmquist productivity index that was introduced as a theoretical index by Caves et al. (1982) and developed and popularized as an empirical index by Färe et al. (1994a, 1994b). Compared to other indices, Malmquist productivity index has some desirable properties which are highly useful in empirical work (see e.g. Färe et al., 1998). For example, it does not require price information or behavioral assumptions such as cost minimization, which implies that it can be used in situations where either prices do not exist or where existing prices have little economic meaning. Perhaps a yet more important property of Malmquist productivity index is that it can be decomposed into economically relevant sources of productivity change. Related to this, Färe et al. (1994a, 1994b) showed how Malmquist productivity index can be expressed as the product of an *efficiency change* index and a *technical change* index, which measure the extent to which productivity changes are due to changes in efficiency and technology, respectively.[11] Later

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[11] Nishimizu and Page (1982) first identified technical change and efficiency change as two distinct components of productivity change.

Färe et al. (1997) further extended this decomposition by showing that technical change index can be expressed as a product of the magnitude change index, an output bias index and an input bias index. We will apply these decompositions to our framework.

Originally, Malmquist (1953) proposed a quantity index for measuring the standard of living in the context of consumption analysis, but later on the Malmquist index and its variations have mainly been used in the field of production analysis. However, most of these studies have concentrated on total factor productivity (TFP) measurement, although in the spirit of the original proposition Malmquist indices could be applied in other areas equally well. Studies by Kumar and Russell (2002) and Cherchye et al. (2006) are, in fact, good examples of this. The former applies Malmquist productivity index to labour productivity measurement, whereas the latter applies a variation of Malmquist output quantity index to the dynamic performance assessment of EU Internal Market effects. While we apply Malmquist productivity index instead of the output index, the approach of Cherchye et al. has some similarities to ours, because it is also based on the benefit of the doubt weighting method and does not consider physical inputs and outputs, but aggregation of different indicators.

There also exists a number of dynamic performance studies that account for undesirable outputs or emissions and utilize Malmquist or Malmquist-Luenberger productivity indices. However, all these studies measure either environmental sensitive total factor productivity (e.g. Chung et al, 1997; Hailu and Veeman, 2000; Weber and Domazlicky, 2001) or the effect of including undesirable outputs to the TFP measure (e.g. Jeon and Sickles, 2004; Managi et al., 2005; Managi, 2006), whereas our approach does not have a link to TFP measurement. From the different techniques presented in literature, our approach is closest to index number approach first developed by Färe et al. (1999, 2004a) and then applied by Zaim et al. (2001), Färe et al. (2004b) and Zaim (2004). Although this technique measures environmental performance, not environmental sensitive productivity, our approach diverges from it in many important respects. Most important difference is that we base our approach on the definition of eco-efficiency, and thus, do not consider traditional inputs and outputs, but value added and environmental pressures, whereas inputs and outputs are the key building blocks of the index number approach. Second main difference to index number approach and most other environmental performance techniques based on productive frontier methods is that we utilize environmental impact assessment methods in constructing environmental pressure categories. Thus, by concentrating on environmental problems we approach environmental performance assessment from a more aggregated perspective than is typically done in productivity and efficiency analysis literature.[12] Due to these reasons, our dynamic approach lies much closer to ecological economics literature than the other techniques based on productivity indices.

3.2. Environmental performance index (EPI)

Malmquist productivity index approach is usually based either on ratios of Shepard's output distance functions or on ratios of input distance functions. Following Färe et al. (1994b), both input- and output-oriented Malmquist productivity indices are typically defined on a benchmark technology satisfying constant returns to scale (CRS). Note that input- and output-oriented Malmquist productivity indices yield identical results under constant returns to scale, and therefore it does not in principle matter which one is used. Although Malmquist productivity index is typically defined by means of distance functions, due to duality we can equally well use a weighting method and define the productivity index as a ratio of efficiency scores. Thus, the proposed *environmental performance index* (EPI) is constructed by using eco-efficiency scores given by the benefit of the doubt weighting approach.

To present our approach formally, we need some additional notation. Let $EE_k(\mathbf{Z}^s, V^s, t)$ denote the relative eco-efficiency measure of production unit *k* observed in period s, measured relative to the frontier of period *t*, calculated as follows

$$
\begin{aligned}
&\left[EE_k(\mathbf{Z}^s, V^s, t)\right]^{-1} = \min_w \; w_1 \frac{Z_{k1}(s)}{V_k(s)} + w_2 \frac{Z_{k2}(s)}{V_k(s)} + \ldots + w_M \frac{Z_{kM}(s)}{V_k(s)} \\
&s.t. \\
&w_1 \frac{Z_{n1}(t)}{V_1(t)} + w_2 \frac{Z_{n2}(t)}{V_1(t)} + \ldots + w_M \frac{Z_{nM}(t)}{V_1(t)} \geq 1, \qquad \forall n = 1, \ldots, N \\
&w_m \geq 0 \qquad\qquad\qquad\qquad\qquad\qquad \forall m = 1, \ldots, M.
\end{aligned}
\tag{5}
$$

where symbols in brackets (i.e. after Z_{km} and V_k) refer to the period of observation. To measure the change of environmental performance in unit *k* from period *t*–1 to *t*, we can take the frontier of period *t* as the benchmark and quantify environmental performance change by ratio of relative eco-efficiency scores based on adjacent observations. Formally

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[12] Third mainly technical difference to index number approach is that we apply Malmquist productivity index, whereas the index number approach is based on a variation of Hicks-Moorsteen productivity index.

(6) $$EPI_k(t) = \frac{EE_k(\mathbf{Z}^t, V^t, t)}{EE_k(\mathbf{Z}^{t-1}, V^{t-1}, t)},$$

where EPI_k means environmental performance index of unit k and t in brackets is the period of reference technology. However, we could equally well choose the frontier of period t–1 as a benchmark, and use the following environmental performance change measure

(7) $$EPI_k(t-1) = \frac{EE_k(\mathbf{Z}^t, V^t, t-1)}{EE_k(\mathbf{Z}^{t-1}, V^{t-1}, t-1)}.$$

Drawing analogy from index theory, the former measure can be seen as a Laspeyres index while the latter one is a Paasche index. Since the two indices are not necessarily equal and we have no reason to prefer period t or t-1 as a benchmark, we follow the conventionally used approach by Fisher (1922) and take the geometric average of the two measures to resolve the issue, which gives

(8) $$EPI_k(t-1,t) = \left(\frac{EE_k(\mathbf{Z}^t, V^t, t-1)}{EE_k(\mathbf{Z}^{t-1}, V^{t-1}, t-1)} \times \frac{EE_k(\mathbf{Z}^t, V^t, t)}{EE_k(\mathbf{Z}^{t-1}, V^{t-1}, t)} \right)^{1/2}, \quad t = 2,...,T.$$

This proposed environmental performance index (EPI) is analogous to the input-oriented Malmquist productivity index presented in productive efficiency literature, although in the present context it measures environmental performance, not traditional or environmental sensitive productivity. Values greater than one indicate improvement of environmental performance in time, while values less than one indicate deterioration in environmental performance from period t–1 to t.

3.3. Decomposing Environmental Performance Change

The environmental performance index (8) shows whether the production unit has progressed or not, but does not yet reveal any sources of environmental performance changes. However, following Nishimizu and Page (1982) and Färe et al. (1994b), we can decompose the overall environmental performance change into two sub-components representing changes due to technological progress (or regress) and due to changes in relative eco-efficiency. The change in relative eco-efficiency is represented by the ratio

(9) $$ECOEFF_k(t-1,t) = \frac{EE_k(\mathbf{Z}^t, V^t, t)}{EE_k(\mathbf{Z}^{t-1}, V^{t-1}, t-1)},$$

where both the numerator and denominator include eco-efficiency measures relative to the frontier of the observed period. This ratio can be interpreted as a catching-up measure, as it reveals how production unit's environmental performance has changed relative to benchmarks. It reveals a relative shift of a unit towards or away from the eco-efficiency frontier. If the value is greater than one, it indicates that the unit has caught up its benchmarks in period *t* as compared to *t*–1, i.e. it has moved towards the frontier. Note that if the production unit is eco-efficient in both periods, value is one and unit acts as a benchmark to other units in both periods. However, the value of $ECOEFF_k(t-1,t)$ can be equal to one also in the case of inefficiency, if eco-efficiency scores of adjacent periods are equal.

The effect of technical progress can be measured from the perspective of period *t* observation as

(10) $$TECH_k^t = \frac{EE_k(\mathbf{Z}^t, V^t, t-1)}{EE_k(\mathbf{Z}^t, V^t, t)},$$

where the notation "$_k^t$" refers to the production unit *k* in period t. As the evaluated point is the same in numerator and in denominator, (10) measures the shift in the frontier with respect to this point. If there is technical progress between periods, efficiency score of numerator is greater than score in denominator. Hence, values greater than one are attributable to technical progress, while values less than one are an indication of technical regress. Note that we could equivalently measure technical change from the perspective of period *t*–1 observation. However, since we again do not have any reason to prefer either period *t* or *t*–1 in the observation, we measure technical change by the geometric average

(11) $$TECH_k^{t,t-1} = \left(\frac{EE_k(\mathbf{Z}^{t-1}, V^{t-1}, t-1)}{EE_k(\mathbf{Z}^{t-1}, V^{t-1}, t)} \times \frac{EE_k(\mathbf{Z}^t, V^t, t-1)}{EE_k(\mathbf{Z}^t, V^t, t)} \right)^{1/2}.$$

This technical change index is interesting from an environmental point of view, because it measures shifts in the eco-efficiency frontier or the best possible performance in period *t* as compared to period *t*–1. Thus, the index shows whether the best practice technology relative to which production units are compared is improving, stagnant or deteriorating. Index value greater than one indicates that environmental performance of the most eco-efficient units has improved.

Now by multiplying the technical change and relative eco-efficiency change components, we obtain:

$$EPI_k(t-1,t) = \frac{EE_k(\mathbf{Z}^t, V^t, t)}{EE_k(\mathbf{Z}^{t-1}, V^{t-1}, t-1)} \times \left(\frac{EE_k(\mathbf{Z}^{t-1}, V^{t-1}, t-1)}{EE_k(\mathbf{Z}^{t-1}, V^{t-1}, t)} \times \frac{EE_k(\mathbf{Z}^t, V^t, t-1)}{EE_k(\mathbf{Z}^t, V^t, t)} \right)^{1/2}$$

(12)

$$= ECOEFF_k(t-1,t) \times TECH_k^{t,t-1},$$

which is the same environmental performance index as (8), but now written as a product of two mutually exclusive and exhaustive components, catching up and technical change. Hence, according to this decomposition, environmental performance growth may result from reduced relative inefficiency or improvement of the production technology or both. Note that as the technical change and relative eco-efficiency change components may quite well move in opposite directions, it is, for example, possible that there is simultaneous improvement in overall environmental performance and deterioration in relative performance (i.e. $EPI_k(t-1,t) > 1$ when $ECOEFF(t-1,t) < 1$) or *vice versa*.

Färe et al. (1994b) further decomposed the efficiency change component into a pure technical efficiency component, calculated relative to variable returns to scale frontier, and a scale efficiency component. However, this decomposition of efficiency change component has been subject to some controversy in the literature.[13] Although we have here so far applied the decomposition of Färe et al. (1994b), we do not decompose the relative eco-efficiency index (i.e. the first component of (13)) further. We think that in the case of eco-efficiency measurement scale efficiency is a non-relevant concept. Even if environmental pressures would depend on the total amount of value added (or output) due to economies or diseconomies of scale, there is no justified reason to separate scale efficiency component from the overall environmental performance change. Thus, we evaluate relative eco-efficiency with respect to frontier performance of optimal scale. Or interpreted alternatively, we measure eco-efficiency per unit of value added, rather than efficiency of the unit

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[13] The decomposition was first criticized by Ray and Desli (1997) and then by many other authors. Because of the problems related to this decomposition, some authors have also suggested alternative decompositions (see Lovell, 2003).

as a whole. This is in line with the eco-efficiency thinking presented by many authors according to which one should pursue to reduce environmental pressures per one unit of economic value added.

3.4. Decomposition of technical change component

Let us next consider the technical change component of (12). Färe et al. (1997) presented an extended decomposition of Malmquist productivity index where technical change index is expressed as the product of a magnitude index and a bias index, where the first component measures technical change from the perspective of period *t*–1 observation, and the second the possible bias in technical progress. Further, they showed that the bias index can yet be expressed as the product of an output bias index and an input bias index. The main motivation for this new decomposition was the fact that earlier decompositions did not have a component for non-neutral technical change, which had been observed as an important reason for productivity growth in many empirical studies. Although our framework is not related to TFP measurement, we think that by applying this decomposition we can obtain important information for dynamic environmental performance analysis.

The decomposition of technical change into a magnitude index and a bias index does not require solving any additional linear programming problems; only the earlier solved efficiency scores are needed. However, when there are multiple inputs and outputs, further decomposition of the bias index into an output and input bias index requires some additional calculation. In the present case there is only one output, economic value added, which implies that the output bias index equals unity, and further, that the general bias index and the input bias index are numerically the same (see the proposition 1 in Färe et al., 1997). Hence, the technical change index can be expressed as follows:

$$
\begin{aligned}
TECH_k^{t,t-1} &= \left[\frac{EE_k(\mathbf{Z}^{t-1}, V^{t-1}, t-1)}{EE_k(\mathbf{Z}^{t-1}, V^{t-1}, t)} \right] \times \left[\frac{EE_k(\mathbf{Z}^{t}, V^{t}, t-1)}{EE_k(\mathbf{Z}^{t}, V^{t}, t)} \Big/ \frac{EE_k(\mathbf{Z}^{t-1}, V^{t-1}, t-1)}{EE_k(\mathbf{Z}^{t-1}, V^{t-1}, t)} \right]^{1/2} \\
&= MATECH_k \times EBIAS_k,
\end{aligned}
\qquad (13)
$$

where the first component $MATECH$ is a magnitude index and the second component $EBIAS$ is a so-called *environmental bias index*, which in the present case is analogous both to general bias index and to input bias index.

By interpretation, *MATECH* measures the magnitude of technical change by using data only from period *t*–1, while *EBIAS* measures the bias of technical change as a ratio of the magnitude of technical change based on the observation of period *t* to the magnitude of technical change based on the period *t*–1 observation. Geometrically, the environmental bias index measures the change in the relative distance between frontiers of period *t* and *t*–1 using adjacent observations. If the magnitude of technical change is the same for period *t* and period *t*–1 observations, then *EBIAS* equals to one and makes no contribution to environmental performance change. This means that technical change is Hicks-neutral in the sense that progress is unbiased with respect to individual environmental pressures. Instead, if the value of *EBIAS* is greater or less than 1, technical change has not been equal among different environmental pressures. For example, greater relative reduction in the amount of carbon dioxide equivalents per one unit of value added compared to other pressures for the production units on the eco-efficient frontier would imply environmental bias in technical change. Of course, in empirical applications one could examine the possible underlying sources of biased technical change in more detail. However, in general we believe that the environmental bias index can provide important information concerning the nature of technical progress.

4. Environmental performance of EU countries

4.1. Background

The monitoring and analysing of countries' environmental performance is generally seen as an important task. Still, most of the earlier studies that have concentrated on measuring environmental performance at the country level have included only few individual pollutants in analysis (see e.g. Zaim and Taskin, 2000; Färe et al., 2004a; Färe et al., 2004b). Besides data availability, one important reason for this has been the discriminatory power of the used methods; many DEA based approaches used in the earlier studies typically lose their power if number of emissions is notably increased. Compared to these previous approaches, the presented framework enables us to include greater number of pollutants in environmental performance assessment without losing the discriminatory power of the method.[14] Recognizing this, in this section we apply the presented technique for calculating an environmental performance index and its components for a sample of 21 EU countries during the period 1990-2000 by accounting for 12 different air pollutants. Our

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[14] This mainly results from environmental impact assessment that we use for aggregating certain individual pollutants into broader environmental pressure categories.

sample includes the following EU25 countries with the abbreviations: Austria (AUT), Belgium (BEL), Czech Republic (CZE), Denmark (DEN), Spain (ESP), Finland (FIN), France (FRA), Germany (GER), Greece (GRE), Hungary (HUN), Ireland (IRL), Italy (ITA), Latvia (LAT), Luxembourg (LUX), Netherlands (NED), Poland (POL), Portugal (POR), Slovenia (SLO), Sweden (SWE), Slovakia (SVK) and United Kingdom (UK).[15]

The focus of the application will be on air pollution mainly because of its international importance and transboundary character. In fact, today the regulation of air pollutant emissions may be the most important environmental policy issue in developed countries. Related to this, there are many international environmental agreements concerning air pollution, some of which are legally binding. The most well-known legally bind agreements include the 1979 Geneva Convention on Long-range Transboundary Air Pollution Reduction Protocol (including 8 specific protocols) and the 1997 Kyoto Protocol to the United Nations Framework Convention on Climate Change. For EU countries, EU directives also have a notable impact on emissions and concentrations of air pollutants. Yet, before early nineties, EU policy concerning air pollution was fragmented and there were only some standards for a few selected air pollutants. The 5th Environmental Action Program 5EAP ("Towards Sustainability") in 1993 was the first program that set longer term environmental objectives in a more integrated approach both for air quality and acidification (CEC, 1993). Among others, 5EAP set emissions ceilings for sulphur dioxide (SO_2), nitrogen dioxide (NO_2) and carbon dioxide (CO_2). The effect of these ceilings on emission levels is interesting from the perspective of the sample period (1990-2000) considered here, because ceilings had to be met by 2000. Besides EU environmental policy and its targets, the 1997 Kyoto Climate Protocol may have affected the amounts of green house gases in the end of the sample period. According to Kyoto Protocol, European Union as a whole should reduce greenhouse gas emissions by 8 per cent from the level of 1990 to the average in the period 2008-2012.

It should be remembered that environmental agreements and regulation do not generally have an effect only on the amounts of specific regulated emissions (such as CO_2), but also indirectly on the economic growth as well as the level of other emissions. For example, policies that reduce carbon dioxide emissions can simultaneously reduce sulphur dioxide emissions, but also increase some other emissions. Therefore, it is important to account for economic value added and several different emissions when measuring environmental performance. Indeed, our purpose is not to concentrate on analysing changes of individual emissions or greenhouse gases, but by applying the

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[15] From EU25 countries, Malta, Estonia, Lithunia and Cyprus were excluded because of insufficient data.

presented methods get insight of changes in overall environmental performance among EU member countries. Further, it is interesting to examine if there has been considerable changes in the performance of individual countries and possible convergence between countries from 1990 to 2000.

4.2. Data and variables

Our value added measure is real gross domestic product (GDP) and for environmental pressure data we use various air pollutant emissions. Real gross domestic product data are taken from the Penn World Tables and measured in purchasing power parity adjusted international prices (base year 1996). National emission data are obtained from the European Environmental Agency (EEA) and include emissions of 12 different pollutants representing 4 different environmental pressure categories: acidification potential (ACID), global warming potential (GWP), tropospheric ozone forming potential (TOFP) and particulate formation (PM10).[16] Although the data is rich with respect to air pollutants, we should note that individual pollutants and gases will have uncertainties in their annual emissions estimates. This uncertainty varies between pollutants; for example, while emissions of CO_2 and SO_2 can be measured or evaluated quite precisely, uncertainty in emission levels of NH_3, VOC and CH_4 can be considerable. On the other hand, although the absolute annual values should include measurement error, changes in emissions can in general be measured more accurately (see de Leeuw, 2002). In this vein, we think that it is reasonable to include also the emissions with a higher level of uncertainty in the dynamic environmental performance analysis. Moreover, we believe that the exclusion of these emissions, as is done in most other studies, would yield a too limited view of the countries' environmental performance. Table 1 lists the different pollutants and corresponding environmental pressure categories that are used in the application.

Following Table 1, we can aggregate individual pollutants into environmental pressure indicators by using scientifically valid conversion factors from environmental impact assessment studies. Note that as some individual emissions such as NO_x and SO_2 cause different types of pressures, they are accounted for in several pressure indicators. The used conversion factors are from Houghton et al. (1996) and de Leeuw (2002) and they are presented in Appendix. It should be remembered that although the conversion factors enable us to account for the relative damage impact of individual pollutants, environmental pressures represent potential not true environmental impacts.

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[16] Data can be downloaded from: http://themes.eea.europa.eu/Specific_media/air/data.

Table 1. Individual pollutants and environmental pressures considered in the study

Pollutants*	**Environmental pressure**	**Unit of measurement**
NO_x, NH_3, SO_2,	Acidification potential (ACID)	Tons of acidification potential equivalents
CO_2, CH_4, HFC-A (CO2-eq), N_2O, PFC-A (CO2-eq), SF_6-A	Global warming potential (GWP)	Tons of CO_2 equivalents
CH_4, CO, NMVOC, NO_x	Tropospheric ozone forming potential (TOFP)	Tons of TOFP equivalents
NO_x, NH_3, PM10, SO_2	Particulate formation (PM10)	Tons of particulate formation equivalents

**Explanations:* NO_x = nitrogen oxides, NH_3 = ammonia, SO_2 = sulfur dioxide, CO_2 = carbon dioxide, CH_4 = methane, HFC = hydro fluor carbon, N_2O = nitrous oxide, PFC = per fluor carbon, SF_6 = sulfur hexafluoride, CO = carbon monoxide, NMVOC = non-methane volatile organic compounds, PM10 = particulate matter particles <10um.

Table 2. Percentage changes in value added and environmental pressures between 1990 and 2000

Country	**Value added**	**ACID**	**GWP**	**TOFP**	**PM10**
AUT	50.8 %	-15.7 %	3.2 %	-23.6 %	-10.3 %
BEL	47.9 %	-31.6 %	1.4 %	-25.3 %	-22.9 %
CZE	20.5 %	-75.5 %	-23.1 %	-44.4 %	-68.5 %
DEN	57.7 %	-40.6 %	-1.5 %	-25.0 %	-35.7 %
ESP	56.2 %	-11.1 %	34.0 %	6.8 %	-4.7 %
FIN	43.0 %	-44.5 %	-0.3 %	-22.1 %	-30.9 %
FRA	41.3 %	-25.2 %	-1.3 %	-29.7 %	-25.3 %
GER	46.1 %	-66.5 %	-18.3 %	-48.5 %	-62.8 %
GRE	59.2 %	0.0 %	20.9 %	15.0 %	-1.2 %
HUN	28.4 %	-46.9 %	-21.6 %	-22.5 %	-42.1 %
IRL	131.6 %	-6.3 %	27.9 %	-7.9 %	-5.8 %
ITA	38.4 %	-35.2 %	7.8 %	-26.6 %	-33.9 %
LAT	-23.4 %	-74.3 %	-60.8 %	-43.7 %	-66.5 %
LUX	144.1 %	-35.4 %	-25.3 %	-37.9 %	-38.4 %
NED	59.7 %	-39.6 %	1.1 %	-36.5 %	-36.2 %
POL	66.8 %	-46.6 %	-16.0 %	-37.4 %	-41.1 %
POR	65.9 %	1.0 %	35.0 %	8.4 %	9.2 %
SLO	51.1 %	-38.4 %	2.2 %	-8.9 %	-32.4 %
SWE	38.4 %	-28.5 %	-6.8 %	-34.5 %	-33.6 %
SVK	14.5 %	-68.0 %	-33.5 %	-56.3 %	-60.6 %
UK	58.0 %	-52.7 %	-12.9 %	-42.4 %	-49.2 %
Mean	**48.0 %**	**-44.5 %**	**-6.2 %**	**-32.1 %**	**-39.5 %**

Table 2 illustrates the data used in the environmental performance calculations by presenting the percentage changes between 1990 and 2000 for value added and environmental pressures for each country.[17] The data show that value added has increased and ACID, TOFP and PM10 have decreased for most of the countries during this period. In contrast, the development with respect to GWP has not been equally satisfactory, because on average CO_2 equivalents have decreased only moderately and for 10 of the countries the amount of CO_2 equivalents is even higher in 2000 than in 1990. Furthermore, the growth of GWP has been considerable for some countries: at worst over 30% for Spain and Portugal. However, it should be mentioned that there is yet quite a lot of variability in GWP changes among countries. Opposite to Spain and Portugal, Latvia and Slovakia for instance had an over 30% decrease in the amount of greenhouse gases during the period studied. Interestingly, there is even more variation in value added; percentage changes range from -23.4% of Latvia to 144.1% of Luxembourg.

4.3. Results and discussion

We first consider relative eco-efficiency scores calculated relative to each year's frontier as outlined in Section 2. Table 3 lists both average eco-efficiency scores and scores in years 1990 and 2000 for each country. For individual years there were in minimum two countries (1992 and 1993) and in maximum five countries (1997) with the score of one. Remarkably, Sweden is the only one on the efficient frontier each year, though also Austria was efficient in all years apart from the last one. The third well-performing country was Germany that was on the frontier every year between 1994 and 2000. In contrast, Poland was the most inefficient country each year with the average eco-efficiency of 0.35. Other poorly ranked countries include Czech Republic, Slovakia and Latvia. It is also interesting to note that for some countries eco-efficiency score in 1990 is notably different than in 2000. For example, for Spain and Greece eco-efficiency is considerably lower in 2000 compared to 1990, while for Luxembourg and United Kingdom the situation is reverse.

To investigate the relationship between eco-efficiency and income, we also calculated Pearson correlation coefficient between eco-efficiency scores and real cross domestic product per capita for each year separately. Values of correlation coefficients ranged from 0.53 in 1990 to 0.75 in 1997 (in 2000 correlation was 0.72). However, although there seems to be clear positive relationship between eco-efficiency scores and income, high value for GDP per capita does not yet imply good

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[17] Appendix presents corresponding absolute values of value added (in billion dollars), ACID (in tons), GWP (in Megatons), TOFP (in Megatons) and PM10 (in Megatons) for all countries in years 1990 and 2000.

environmental performance or *vice versa*. For example, in 1990 Luxembourg had a highest GDP per capita value and it is yet ranked 17th in eco-efficiency comparison with the score of 0.68. On the other hand, Germany's eco-efficiency score in 2000 is equal to one, although it has only tenth largest value for GDP per capita.

Table 3. Relative eco-efficiency scores

	Eco-efficiency scores			**No. of times in eco-efficiency frontier**
Country	**1990**	**2000**	**Average eco-efficiency**	
AUT	1.00	0.98	1.00	10
BEL	0.87	0.72	0.85	1
CZE	0.52	0.44	0.47	0
DEN	0.78	0.81	0.73	0
ESP	0.90	0.67	0.82	0
FIN	0.71	0.65	0.63	0
FRA	0.95	0.91	0.93	0
GER	0.83	1.00	0.97	7
GRE	0.70	0.47	0.57	0
HUN	0.72	0.54	0.62	0
IRL	0.72	0.68	0.67	0
ITA	1.00	0.89	0.96	3
LAT	0.54	0.61	0.52	0
LUX	0.68	1.00	0.81	4
NED	1.00	0.95	0.96	2
POL	0.35	0.40	0.35	0
POR	0.88	0.69	0.80	0
SLO	0.87	0.68	0.69	0
SWE	1.00	1.00	1.00	11
SVK	0.53	0.59	0.50	0
UK	0.70	0.87	0.77	0
Mean	**0.77**	**0.74**	**0.75**	

We next examine the dynamic performance of the countries by means of EPI and its components. Figure 1 presents the annual average changes of environmental performance and its subcomponents.[18] Interestingly, changes in environmental performance and technical change have been positive (i.e. index value is greater than one) through the period studied, whereas relative eco-efficiency change has been positive in six but negative in four years. Further, average eco-efficiency change for the whole period is -0.5%, while the corresponding average technical change and average overall change are 7% and 6.4%, respectively. As can be seen, these average results seem

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[18] Note that all the presented average values are geometric means, since environmental performance index is multiplicative.

to show that technical progress is the key factor for environmental performance growth. However, note that rate of technical change is approximately the same at the beginning and at the end of the period, whereas environmental performance growth rate has been ascending starting from 4.3% in 1990-1991 and ending at 8.5% in 1999-2000.

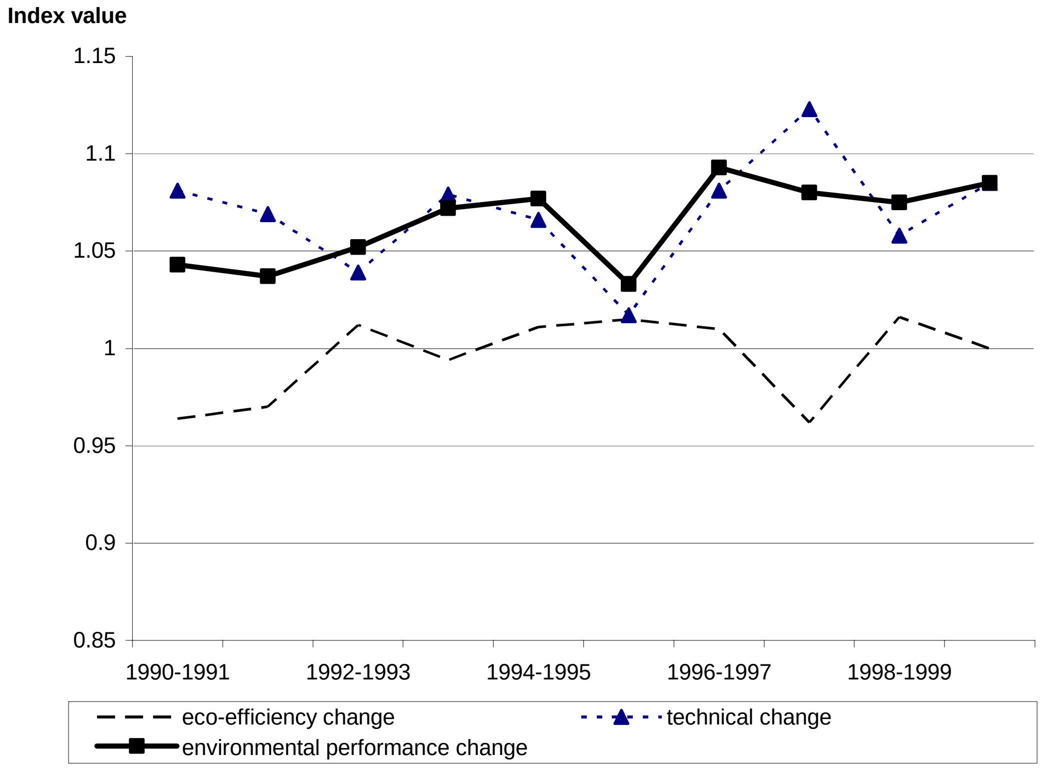

Figure 1. *Average annual changes in environmental performance and in its components in 1990-2000*

We report average values of individual countries' environmental performance index and its components in Table 4. Generally, country-level results seem to show the same kind of pattern as Figure 1: for all countries it is indeed technical change that mostly explains environmental performance growth. Noteworthily, for Luxembourg and Germany environmental performance has increased the most, whereas for Spain and Portugal the growth has been lowest in the sample. By looking back at Table 1, this result is not surprising, because in Spain and Portugal the absolute level of greenhouse gases has increased most among the sample countries. In addition, both are also in top-three with respect to the growth of TOFP, and Portugal is the only country with a positive change in PM10. Instead, environmental performance growth of Germany is predominantly explained by its top-three performance regarding the reduction of ACID, TOFP and PM10.

Table 4. Environmental performance change and its components in 1990-2000

	Average values			
Country	**Environmental performance change**	**Eco-efficiency change**	**Technical change**	**Ranking with respect to EPI**
AUT	1.06	1.00	1.06	12
BEL	1.07	0.98	1.09	9
CZE	1.07	0.99	1.09	8
DEN	1.06	1.00	1.05	11
ESP	1.02	0.97	1.05	21
FIN	1.05	0.99	1.05	16
FRA	1.05	1.00	1.05	15
GER	1.11	1.02	1.09	2
GRE	1.03	0.96	1.07	19
HUN	1.05	0.97	1.08	13
IRL	1.09	0.99	1.10	5
ITA	1.04	0.99	1.05	18
LAT	1.07	1.01	1.05	10
LUX	1.14	1.04	1.10	1
NED	1.10	0.99	1.10	3
POL	1.09	1.01	1.08	4
POR	1.03	0.98	1.05	20
SLO	1.04	0.98	1.07	17
SWE	1.05	1.00	1.05	14
SVK	1.08	1.01	1.07	6
UK	1.08	1.02	1.05	7
Mean	**1.06**	**1.00**	**1.07**	

When considering the values of eco-efficiency changes, we can observe that there are no great differences between countries; the lowest and highest values are 0.96 (Greece) and 1.04 (Luxemburg), respectively. For seven out of 21 countries the average eco-efficiency change has been positive (i.e. over one), which means that they have caught up the eco-efficient benchmarks. In contrast to efficiency changes, average technical change contributes extensively to environmental performance growth, as each country's value deviates clearly from one. Nevertheless, it is important to remember that technical change basically describes the change of the frontier, i.e. the best performers of the sample, not the development of the countries under the frontier. Hence, here the value of technical change predominantly reveals how environmental performance of Sweden, Austria and Germany has developed.

Following the presented methodology, we also decomposed technical change component into a magnitude change index and environmental bias index (for more detailed results, see Appendix). The average value of the bias index in the sample was 1.00, which suggests that the bias has no effect on the observed growth. Furthermore, country-level average values did not differ substantially from 1 either - changes range from -0.16% to 1.46%. Thus, we can conclude that the bias effect for environmental performance growth has been negligible for EU countries during the sample period.

To sum up, here we have considered dynamic environmental performance analysis of EU countries by calculating EPI and its components as presented in Section 3. It would yet be interesting to examine possible determinants for the overall and individual countries' performance changes using regression analysis. This second-stage analysis could be done by applying a sophisticated two-stage bootstrap estimation procedure recommended by Simar and Wilson (2006) or alternatively by using Generalized Method of Moments approach suggested by Zhengfei and Oude Lansink (2006). Factors that could possibly explain changes of environmental performance include among others GDP per capita, capital stock per labour, climate and demographic variables such as population and population density. In general, it would also be interesting to examine what kinds of effects environmental agreements and their ratification have on the environmental performance growth. However, as we think that this second-stage analysis concerning the determinants of environmental performance growth would require a more extensive and thorough treatment we leave it as a question for future research.

5. Conclusions

We have presented a new method for dynamic eco-efficiency analysis that applies benefit of the doubt weighting and Malmquist index. We constructed an environmental performance index (EPI) and showed how it can be decomposed into technical change and relative eco-efficiency components. We further demonstrated that technical change index can yet be expressed as a product of magnitude change index and environmental bias index. These different components of EPI can be highly useful when analyzing sources and reasons for changes in environmental performance over time.

Importantly, in contrast to other dynamic methods based on the used techniques, our approach is consistent with the definition of eco-efficiency as a ratio of economic valued added to environmental damage index. A further link to ecological economics and industrial ecology is the environmental impact assessment that we utilize for aggregating emissions of individual pollutants into environmental pressures. Thus, the approach presented in this paper can be seen as a further step towards integrating the perspectives of ecological economics and the frontier approach of environmental performance assessment into a unified framework. We think that the presented method provides both interesting insights for the literature of environmental performance analysis and also many application possibilities.

We applied the proposed methodology to dynamic environmental performance analysis of 21 EU countries in 1990-2000. According to the country-level results, for most countries changes in relative eco-efficiency have been minor during the sample period whereas technical progress has been the key factor for environmental performance growth. Further decomposition of technical change revealed that the bias effect has been negligible for all countries.

Although the technique was here used for a cross-country comparison, one of the method's advantages is indeed its applicability at any level of aggregation from firm and industry level studies to cross-country comparisons. One interesting direction for further research would be to examine environmental Kuznets type relationship between the environmental performance measured by our index and income growth. Most of the studies that have estimated Environmental Kuznets Curve have used only one emission at a time. The presented framework would enable us to estimate Environmental Kuznets Curve that accounts for large number of different emissions simultaneously.

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APPENDIX

Table A1. Conversion factors for air pollutants

Pollutant	Environmental pressures	Conversion factors*	Measurement units
NO_x	Acidification	0.021739	Tons of acidifying potential eq.
SO_2	Acidification	0.031250	Tons of acidifying potential eq.
NH_3	Acidification	0.058824	Tons of acidifying potential eq.
CH_4	Global warming potential	21	Tons of CO_2 eq.
CO_2	Global warming potential	1	Tons of CO_2 eq.
HFC-A (CO_2-eq)	Global warming potential	1	Tons of CO_2 eq.
N_2O	Global warming potential	310	Tons of CO_2 eq.
PFC-A (CO_2-eq)	Global warming potential	1	Tons of CO_2 eq.
SF_6-A	Global warming potential	23900	Tons of CO_2 eq.
CH_4	Tropospheric ozone forming potential	0.014	Tons of CO_2 eq.
CO	Tropospheric ozone forming potential	0.110	Tons of TOFP eq.
NMVOC	Tropospheric ozone forming potential	1.000	Tons of TOFP eq.
NO_x	Tropospheric ozone forming potential	1.220	Tons of TOFP eq.
SO_2	Particulate Formation PM10	0.54	Tons of particulate formation eq.
NH_3	Particulate Formation PM10	0.64	Tons of particulate formation eq.
NO_x	Particulate Formation PM10	0.88	Tons of particulate formation eq.
PM10	Particulate Formation PM10	1.00	Tons of particulate formation eq.

* Source: Houghton et al. (1996) and de Leeuw (2002).

Table A2. Value added and environmental pressure data for 1990 and 2000

	Value added (bn $)		ACID (t)		GWP (Mt)		TOFP (Mt)		PM10 (Mt)	
Country	1990	2000	1990	2000	1990	2000	1990	2000	1990	2000
AUT	133.6	201.4	10329.5	8708.1	78.6	81.1	0.7	0.5	0.3	0.3
BEL	173.4	256.4	25471.7	17433.5	145.7	147.7	1.0	0.8	0.6	0.5
CZE	126.6	152.5	79783.8	19581.2	192.1	147.6	1.3	0.7	1.6	0.5
DEN	96.6	152.3	19523.0	11598.8	69.3	68.3	0.7	0.5	0.5	0.3
ESP	486.6	760.1	114150.8	101491.2	283.9	380.5	3.1	3.3	2.7	2.6
FIN	88.4	126.4	16882.0	9376.5	70.4	70.2	0.7	0.5	0.5	0.3
FRA	1009.8	1427.0	127619.0	95469.5	568.0	560.4	5.9	4.1	3.4	2.6
GER	1345.0	1965.2	271607.7	91101.9	1243.6	1016.6	8.3	4.3	5.9	2.2
GRE	103.2	164.3	26357.7	26366.1	109.4	132.3	0.8	0.9	0.7	0.7
HUN	86.4	110.9	44030.5	23389.0	103.3	81.0	0.6	0.5	0.9	0.5
IRL	44.5	103.0	14982.3	14031.6	53.9	69.0	0.3	0.3	0.3	0.3
ITA	953.9	1320.6	122513.9	79406.2	511.2	551.3	5.2	3.8	3.2	2.1
LAT	25.7	19.7	7681.6	1973.9	25.4	9.9	0.3	0.2	0.2	0.1
LUX	8.9	21.6	1380.5	892.3	12.7	9.5	0.1	0.0	0.0	0.0
NED	256.8	410.0806	32721.9	19757.6	211.7	214.0	1.3	0.8	0.8	0.5
POL	223.8	373.4	158020.9	84377.3	459.8	386.2	3.2	2.0	3.5	2.0
POR	103.0	170.975	21541.9	21760.4	59.4	80.1	0.7	0.7	0.6	0.6
SLO	22.3	33.8	8906.3	5482.1	18.6	19.0	0.1	0.1	0.2	0.1
SWE	157.8	218.4789	13579.2	9702.9	72.2	67.3	1.0	0.7	0.5	0.3
SVK	59.5	68.2	25339.0	8111.2	72.1	47.9	0.6	0.3	0.6	0.2
UK	917.0	1449.2	199230.9	94229.6	748.0	651.5	6.8	3.9	5.0	2.5
Mean	305.8	452.6	63888.3	35440.0	243.3	228.2	2.0	1.4	1.5	0.9

Table A3. Technical change index and its subcomponents in 1990-2000

	Average values		
Country	**Technical change**	**Magnitude change**	**Environmental bias**
AUT	1.06	1.04	1.01
BEL	1.09	1.08	1.00
CZE	1.09	1.09	1.00
DEN	1.05	1.05	1.00
ESP	1.05	1.06	1.00
FIN	1.05	1.05	1.00
FRA	1.05	1.05	1.00
GER	1.09	1.08	1.01
GRE	1.07	1.07	1.00
HUN	1.08	1.08	1.00
IRL	1.10	1.09	1.00
ITA	1.05	1.05	1.00
LAT	1.05	1.05	1.00
LUX	1.10	1.09	1.01
NED	1.10	1.10	1.00
POL	1.08	1.08	1.00
POR	1.05	1.06	1.00
SLO	1.07	1.06	1.00
SWE	1.05	1.04	1.01
SVK	1.07	1.07	1.00
UK	1.05	1.05	1.00
Mean	**1.07**	**1.07**	**1.00**