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## Determining drivers of eco-efficiency: decomposition method

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### WP No. 7

### **Determining drivers of eco-efficiency: decomposition method**

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# Determining drivers of eco-efficiency: decomposition method<sup>1</sup>

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## Abstract

There has been a lively discussion about measures of social welfare *beyond GDP* induced by *Stiglitz Report* (Stiglitz et al, 2009) which can be viewed as a summation of the earlier efforts to deal with those challenges. Environmental indicators constitute one important dimension to be taken into account in assessing the welfare along with the economic and social indicators. Employing non-parametrical approach, the Data Envelopment Analysis SBM model is extended for environment to measure the so called eco-efficiency. Resulting scores and benchmarks are used to decompose eco-productivity into factors attributable to changes in efficiency, technology, extensive factors of production, and emissions. Results suggest that in European countries in the span 2000 – 2010, an environment-saving rather than input-saving technology change has been taking place.

**Keywords:** eco-efficiency, data envelopment analysis, beyond GDP, decomposition

**JEL codes:** C43, C61, O47

## 1 Introduction

There has been a lively discussion about measures of social welfare *beyond GDP* induced by *Stiglitz Report* (Stiglitz et al, 2009) which can be viewed as a summation of the earlier efforts to deal with those challenges. Environmental indicators constitute one important dimension to be taken into account in assessing the welfare along with the economic and social indicators.

In the practice of economic policy decision making, often the claim for meeting multiple goals occurs. The example be the requirements of the Strategy Europe 2020 which defines benchmarks for social and environmental dimensions while keeping the economy on the growth path. Theoretical support for decision making cannot be based on barely proportional indicators relating to goals which may require conflicting actions.

In this study, we concentrate on environmental aspects of economic growth. The method of evaluating country's performance – data envelopment analysis (DEA) – is employed, assessing economic (technical) and environmental simultaneously. The DEA method allows one to circumvent certain shortcuts of parametric methods, namely only dealing with single output in a production function and need for prices of inputs and outputs as aggregating weights.

There has been an obvious shift in environment-protecting-oriented technology over the last decade or more. One can be interested in the quality of the shift – is the “greener” technology driven by better use of the inputs or is an environment-saving progress going on? Non-parametrical approach is capable of giving answers to such type of questions.

We proceed as follows. Section 2 provides theoretical definitions of the concept of efficiency. Then measurement method as application of linear programming is described, the SBM model is

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particularly paid attention to and the strategy of incorporating undesirable output into the model is presented. Section 3 describes the data used and the model setup. In Section 4, decomposition method of Henderson-Russell (2005) is brought out as a starting point for further extension and use in intertemporal analysis of eco-efficiency change over the span of 2000 and 2010. Section 5 provides results of the actual empirical analysis, gives some comments and Section 6 concludes.

## 2 Measuring eco-efficiency

### 2.1 SBM efficiency measure

The above-mentioned considerations need to be operationalized. First, measurement of efficiency should be introduced. There are several approaches leading to the same evaluation in the form of a linear program. To follow one of them, let's organize data and give some definitions.

Economic subjects under examination be called DMUs (Decision Making Units) to reflect their independent economic behavior. Let's assume to have  $n$  DMUs transforming  $m$  inputs into  $s$  desirable outputs. Inputs are organized in the matrix  $\mathbf{X}$ , element  $x_{ij}$  meaning amount of input  $i$  used by DMU  $j$ , and the similar way in the output matrix  $\mathbf{Y}$ .

$$\mathbf{X} = \begin{bmatrix} x_{11} & x_{12} & \dots & x_{1n} \\ x_{21} & x_{22} & \dots & x_{2n} \\ \vdots & \vdots & \dots & \vdots \\ x_{m1} & x_{m2} & \dots & x_{mn} \end{bmatrix}, \quad \mathbf{Y} = \begin{bmatrix} y_{11} & y_{12} & \dots & y_{1n} \\ y_{21} & y_{22} & \dots & y_{2n} \\ \vdots & \vdots & \dots & \vdots \\ y_{s1} & y_{s2} & \dots & y_{sn} \end{bmatrix}$$

To assess technical efficiency, the general formula can be used:

$$efficiency = \frac{outputs}{inputs} \quad (2.1)$$

In classical DEA, every DMU aggregates its inputs and outputs by means of individually set weights so that the ratio 2.2.1 is maximized. In order to avoid unboundedness of maximization problem, the constraint is imposed so that normalized efficiency cannot exceed unit which also holds in case of using the weights of DMU under consideration (denoted  $DMU_0$ ) for any other of  $n-1$  DMUs. Formally:

$$\max \quad h_0(\mu, \nu) = \frac{\sum_{r=1}^s y_{r0} \mu_r}{\sum_{i=1}^m x_{i0} \nu_i} \quad (2.2)$$

$$\begin{aligned} \text{s.t.} \quad & \frac{\sum_{r=1}^s y_{rj} \mu_r}{\sum_{i=1}^m x_{ij} \nu_i} \leq 1 & (j = 1, 2, \dots, n) \\ & \mu_r \geq 0 & (r = 1, 2, \dots, s) \\ & \nu_i \geq 0 & (i = 1, 2, \dots, m) \end{aligned} \quad (2.3)$$

The fractional program can be transformed into the linear one called CCR model (proposed by Charnes et al, 1978) which was first to evaluate performance in a non-parametric way.

The basic model had been improved and modified many ways. The slack-based model (SBM) by Tone is one of the powerful developments to capture all sources of inefficiency. The objective function has two important properties:

- unit invariance
- monotonicity.

A function  $\rho = \frac{1 - \frac{1}{m} \sum_{i=1}^m s_i^- / x_{i0}}{1 + \frac{1}{s} \sum_{r=1}^s s_r^+ / y_{r0}}$  meet the requirements of the both, moreover, it can be shown

that  $0 < \rho \leq 1$  (Cooper et al, 2007, p.100).

Evaluation of efficiency takes the form of a fractional program:

$$\begin{aligned} \min_{\lambda, s^+, s^-} \quad & \rho = \frac{1 - \frac{1}{m} \sum_{i=1}^m s_i^- / x_{i0}}{1 + \frac{1}{s} \sum_{r=1}^s s_r^+ / y_{r0}} \\ \text{s.t.} \quad & \mathbf{x}_0 = X\lambda + \mathbf{s}^- \\ & \mathbf{y}_0 = Y\lambda - \mathbf{s}^+ \\ & \lambda \geq 0, \mathbf{s}^- \geq 0, \mathbf{s}^+ \geq 0. \end{aligned} \quad (2.4)$$

Using substitution  $t = \frac{1}{1 + \frac{1}{s} \sum_{r=1}^s s_r^+ / y_{r0}}$  one can obtain a linear program :

$$\begin{aligned} (SBMt) \quad \min_{t, \lambda, s^+, s^-} \quad & \tau = t - \frac{1}{m} \sum_{i=1}^m t s_i^- / x_{i0} \\ \text{s.t.} \quad & \mathbf{x}_0 = X\lambda + \mathbf{s}^- \\ & \mathbf{y}_0 = Y\lambda - \mathbf{s}^+ \\ & \lambda \geq 0, \mathbf{s}^- \geq 0, \mathbf{s}^+ \geq 0, t > 0 \\ & . \end{aligned} \quad (2.5)$$

Substituting  $t\mathbf{s}^- = \mathbf{S}^-$ ,  $t\mathbf{s}^+ = \mathbf{S}^+$  a  $t\lambda = \Lambda$ ,  $SBMt$  is converted into

$$\begin{aligned} (SBMt) \quad \min \quad & \tau = t - \frac{1}{m} \sum_{i=1}^m S_i^- / x_{i0} \\ \text{s.t.} \quad & t\mathbf{x}_0 = X\Lambda + \mathbf{S}^- \\ & t\mathbf{y}_0 = Y\Lambda - \mathbf{S}^+ \\ & \Lambda \geq 0, \mathbf{S}^- \geq 0, \mathbf{S}^+ \geq 0, t > 0. \end{aligned} \quad (2.6)$$

The dual linear program associated with  $SBMt$  is

$$\max_{\xi, \mathbf{v}, \mathbf{u}} \quad \xi \quad (2.7)$$

$$\begin{aligned}
\text{s.t.} \quad & \xi + \mathbf{v}\mathbf{x}_0 - \mathbf{u}\mathbf{y}_0 = 1 \\
& -\mathbf{v}X + \mathbf{u}Y \leq \mathbf{0} \\
& \mathbf{v} \geq \frac{1}{m} [1/\mathbf{x}_0] \\
& \mathbf{u} \geq \frac{\xi}{s} [1/\mathbf{y}_0]
\end{aligned}$$

The first constraint enables to write the objective function as  $\max \mathbf{v}\mathbf{x}_0 - \mathbf{u}\mathbf{y}_0$  with the last constraint for  $\mathbf{u}$

$$\mathbf{u} \geq \frac{1 - \mathbf{v}\mathbf{x}_0 + \mathbf{u}\mathbf{y}_0}{s} [1/\mathbf{y}_0].$$

After solving *SBMt* formulated by 2.6 or 2.7, one can go back to  $\mathbf{s}^{0+}$ ,  $\mathbf{s}^{0-}$ ,  $\lambda^0$  as optimal solutions of *SBM* and determine  $\rho^0$  for DMU<sub>0</sub>. Efficient DMUs will have values of  $\rho$  equal unit. Inefficient ones will have  $\rho < 1$  due to positive slack variables  $\mathbf{s}^{0+}$ ,  $\mathbf{s}^{0-}$  which express deviation from the frontier or “potential”. Projections to the frontier are thus given by

$$\begin{aligned}
\hat{\mathbf{x}}_0 &\Leftarrow \mathbf{x}_0 - \mathbf{s}^{-0} \\
\hat{\mathbf{y}}_0 &\Leftarrow \mathbf{y}_0 + \mathbf{s}^{+0}
\end{aligned} \tag{2.8}$$

Indexes of variables  $\lambda_j > 0$  constitute the reference set  $R_0$  (efficiency frontier), every frontier point  $(\mathbf{x}_0^*, \mathbf{y}_0^*)$  being positive linear combination of the other elements of the reference set:

$$\hat{\mathbf{x}}_0 = \sum_{j \in R_0} \mathbf{x}_j \lambda_j, \quad \hat{\mathbf{y}}_0 = \sum_{j \in R_0} \mathbf{y}_j \lambda_j$$

It obvious from the construction of  $\rho$  that it takes into account all the sources of inefficiency and therefore  $\rho_{\text{SBM}} \leq \rho_{\text{CCR}}$ . *SBM* efficient DMUs are also CCR efficient but not the other way round. It is possible to give model input or output orientation in order to reflect preferences and feasibility of the policy. Input orientation is carried out by omitting output *slacks* in (2.2.4):

$$\begin{aligned}
\min \quad & \rho = 1 - \frac{1}{m} \sum_{i=1}^m s_i^- / x_{i0} \\
\text{s.t.} \quad & \mathbf{x}_0 = X\lambda + \mathbf{s}^- \\
& \mathbf{y}_0 = Y\lambda - \mathbf{s}^+ \\
& \lambda \geq 0, \quad \mathbf{s}^- \geq 0, \quad \mathbf{s}^+ \geq 0.
\end{aligned}$$

Output orientation (*SBM-O*) is achieved in a similar way by omitting input *slacks*:

$$\begin{aligned}
\min \quad & \rho = \frac{1}{1 + \frac{1}{s} \sum_{r=1}^s s_r^+ / y_{r0}} \\
\text{s.t.} \quad & \mathbf{x}_0 = X\lambda + \mathbf{s}^- \\
& \mathbf{y}_0 = Y\lambda - \mathbf{s}^+ \\
& \lambda \geq 0, \quad \mathbf{s}^- \geq 0, \quad \mathbf{s}^+ \geq 0.
\end{aligned} \tag{2.9}$$

## 2.2 Modelling undesirable outputs

Once the measure of efficiency has been defined, one can proceed to evaluating eco-efficiency. Individual European countries will be considered as 29 DMUs. As the concept encompasses two dimensions, it's natural to divide the problem of evaluation into two separate parts – economic and “ecological” performance, the former being evaluated using the classical approach described above. In order to assess ecological efficiency, an SBM model can be employed with GDP acting as output and emissions as inputs which is in line with the work of Korhonen and Luptáčík (2004) where such specification is justified along with the assumption of *strong disposability* of outputs. Thus, model denoted *tech* gives values of technical efficiency evaluating use of capital and labor for producing output while model *eco* provides information on the efficient (i.e. as little as possible) “use” of emissions. This is a “pure ecological efficiency” approach of Kuosmanen and Kortelainen (2005). Each model gives values describing the two dimensions. To obtain the overall indicator, the two values have to be combined in a composite model. Such model is constructed by taking *tech* and *eco* scores as outputs for the composite output oriented model, inputs being equal unit. The resulting *eco\_tech* score can be considered a measure of eco-efficiency.

## 3 Data and modelling

For empirical analysis, two standard technical inputs – capital stock (K) measured in mil. EUR and labour (L) in thousands of workers were used. Units of measurement can be arbitrarily chosen since as has been shown in Section 2 SBM models have unit invariance property. The same applies to technical output GDP (Y) measured in mil. EUR. Emissions come in thousands of ton of greenhouse equivalent acting as undesirable output associated with the production. All data come from European databases AMECO and Eurostat. For intertemporal analysis, data from 29 DMUs (European countries) of 2000 and 2010 have been used. Thus  $n=29$ , in linear programs formulated in the previous section. 29 optimizations of the SBM-O-C type given by (2.9) must be computed to obtain efficiency scores of DMUs as well as the potential improvement of desirable output given by projections onto the efficiency frontier for every model specification. Statistical properties of the data used are in Table 1.

**Table 1** Statistics on Input/Output Data

| 2000 |           |         |           |           | 2010 |           |         |          |           |
|------|-----------|---------|-----------|-----------|------|-----------|---------|----------|-----------|
|      | K1        | L1      | E1        | Y1        |      | K2        | L2      | E2       | Y2        |
| Max  | 6012960,0 | 39382,0 | 1038999,0 | 1840730,7 | Max  | 6466000,0 | 40603,0 | 936544,0 | 2028463,7 |
| Min  | 14466,3   | 156,4   | 3845,0    | 7049,8    | Min  | 21078,6   | 167,2   | 4542,0   | 8750,3    |
| Avg  | 1050117,6 | 8079,9  | 191296,3  | 352374,6  | Avg  | 1288951,0 | 8494,5  | 178059,9 | 409727,7  |
| SD   | 1454945,8 | 9769,7  | 245822,9  | 487381,2  | SD   | 1705341,9 | 10264,7 | 222615,3 | 540928,3  |

  

| Correlation |       |       |       |       | Correlation |       |       |       |       |
|-------------|-------|-------|-------|-------|-------------|-------|-------|-------|-------|
|             | K1    | L1    | E1    | Y1    |             | K2    | L2    | E2    | Y2    |
| K1          | 1     | 0,973 | 0,975 | 0,992 | K2          | 1     | 0,979 | 0,964 | 0,994 |
| L1          | 0,973 | 1     | 0,989 | 0,973 | L2          | 0,979 | 1     | 0,989 | 0,985 |
| E1          | 0,975 | 0,989 | 1     | 0,971 | E2          | 0,964 | 0,989 | 1     | 0,973 |
| Y1          | 0,992 | 0,973 | 0,971 | 1     | Y2          | 0,994 | 0,985 | 0,973 | 1     |

Source: author's calculation

As could be expected, the data show quite a big variance due to variability in size of individual economies.

## 4 Decomposition: identifying drivers of eco-efficiency change

Identification of drivers of the eco-efficiency change can be approached by intertemporal analysis. One of the possible attempts could be through Malmquist productivity index and decomposition of the TFP as it was carried out in Mahlberg et al (2011) for example. Another approach makes use of the decomposition method used in productivity studies. We refer to the work of Henderson and Russell (2005) as HR whose analysis constitutes a starting point for further extension. The key purpose of the method is to separately describe three “movements” of the DMU with respect to efficiency boundary over time:

- (1) technology change – *frontier-shift* movement
- (2) *catch-up* – movement towards or away from the frontier
- (3) capital accumulation – movement along the frontier.

Relative magnitude of these effects can help interpret the nature of the technology change – whether there is an input-saving technological improvement exploiting better use of technical inputs to increase eco-efficiency or environment- saving technology which enables to produce more output while reducing pollution.

Setting out in a HR manner, we first define a productivity indicator subject to decomposition. To reflect two-dimensional assessment of economic activity, we define  $y$  as an output-emissions ratio, i.e. output per unit of emissions  $Y/E$ . this can be also interpreted as the reciprocal of pollutants-intensity of production (output). Thus higher values of  $y$  represent greener production. Focusing on the intertemporal change between starting period 1 and the period 2

and indexing variables with respective numbers, the ratio of the interest becomes  $\frac{y_2}{y_1} = \frac{Y_2/E_2}{Y_1/E_1}$ .

Taking into account efficiency scores, actual values can be expressed by means of the benchmarks (potentials) indicated by the bar:

$$\frac{y_2}{y_1} = \frac{e_2}{e_1} \cdot \frac{\bar{y}_2(K_2, L_2, E_2)}{\bar{y}_1(K_1, L_1, E_1)} = \frac{\bar{Y}_2(K_2, L_2, E_2)/E_2}{\bar{Y}_1(K_1, L_1, E_1)/E_1}$$

The following step consists in multiplying numerator and denominator by the terms

$\bar{y}_2(K_1, L_1, E_1)$  and  $\bar{y}_2(K_1, L_1, E_2)$  which would represent potential eco-productivities achievable with the level of emissions of periods 1 and 2, both given factors of production  $K$  and  $L$  of period 1 and the technology of period 2. After rearranging one obtains

$$\begin{aligned} \frac{y_2}{y_1} &= \frac{e_2}{e_1} \cdot \frac{\bar{y}_2(K_2, L_2, E_2)}{\bar{y}_1(K_1, L_1, E_1)} = \frac{e_2}{e_1} \cdot \frac{\bar{y}_2(K_2, L_2, E_2)}{\bar{y}_1(K_1, L_1, E_1)} \cdot \frac{\bar{y}_2(K_1, L_1, E_1)}{\bar{y}_2(K_1, L_1, E_1)} \cdot \frac{\bar{y}_2(K_1, L_1, E_2)}{\bar{y}_2(K_1, L_1, E_2)} \\ &= \frac{e_2}{e_1} \cdot \frac{\bar{Y}_2(K_2, L_2, E_2)/E_2}{\bar{Y}_1(K_1, L_1, E_1)/E_1} \cdot \frac{\bar{Y}_2(K_1, L_1, E_1)}{\bar{Y}_2(K_1, L_1, E_1)} \cdot \frac{\bar{Y}_2(K_1, L_1, E_2)}{\bar{Y}_2(K_1, L_1, E_2)} \\ &= \frac{e_2}{e_1} \cdot \frac{\bar{Y}_2(K_1, L_1, E_1)}{\bar{Y}_1(K_1, L_1, E_1)} \cdot \frac{\bar{Y}_2(K_2, L_2, E_2)}{\bar{Y}_2(K_1, L_1, E_2)} \cdot \frac{\bar{Y}_2(K_1, L_1, E_2)/E_2}{\bar{Y}_2(K_1, L_1, E_1)/E_1} \end{aligned}$$



The resulting expression consists of the four factors that we denote the following way. Superscript is used for benchmark technology. Factor *TECH* compares technologies by relating potential outputs achievable by the same set of inputs and emissions (of period 1 in this case).

$$\frac{y_2}{y_1} = ECOEFF \cdot TECH^1 \cdot KACC_2^2 \cdot EMIS_2^1 [E_2/E_1] \quad (2.10)$$

$$\frac{Y_2}{Y_1} = ECOEFF \cdot TECH^1 \cdot KACC_2^2 \cdot EMIS_2^1 \quad (2.11)$$

Superscript is used to indicate at which period's level have been the other variables kept fixed, e.g.  $KACC_2^2 = \frac{\bar{Y}_2(K_2, L_2, E_2)}{\bar{Y}_2(K_1, L_1, E_2)}$  reflects change in eco-productivity which would be induced by the change in the extensive factors of production while keeping emissions at the level of period 2 under the technology of period 2.

There are four variations of possible decomposition of  $\frac{e_2}{e_1} \cdot \frac{\bar{y}_2(K_2, L_2, E_2)}{\bar{y}_1(K_1, L_1, E_1)}$  which differ in combinations of indices:

$$\begin{aligned} [1] \quad \frac{Y_2}{Y_1} &= \frac{e_2}{e_1} \cdot \frac{\bar{Y}_2(K_1, L_1, E_1)}{\bar{Y}_1(K_1, L_1, E_1)} \cdot \frac{\bar{Y}_2(K_2, L_2, E_1)}{\bar{Y}_2(K_1, L_1, E_1)} \cdot \frac{\bar{Y}_2(K_2, L_2, E_2)}{\bar{Y}_2(K_2, L_2, E_1)} = ECOEFF \cdot TECH^1 \cdot KACC_2^1 \cdot EMIS_2^2 \\ [2] \quad \frac{Y_2}{Y_1} &= \frac{e_2}{e_1} \cdot \frac{\bar{Y}_2(K_1, L_1, E_1)}{\bar{Y}_1(K_1, L_1, E_1)} \cdot \frac{\bar{Y}_2(K_2, L_2, E_2)}{\bar{Y}_2(K_1, L_1, E_2)} \cdot \frac{\bar{Y}_2(K_1, L_1, E_2)}{\bar{Y}_2(K_1, L_1, E_1)} = ECOEFF \cdot TECH^1 \cdot KACC_2^2 \cdot EMIS_2^1 \\ [3] \quad \frac{Y_2}{Y_1} &= \frac{e_2}{e_1} \cdot \frac{\bar{Y}_2(K_2, L_2, E_2)}{\bar{Y}_1(K_2, L_2, E_2)} \cdot \frac{\bar{Y}_1(K_2, L_2, E_2)}{\bar{Y}_1(K_1, L_1, E_2)} \cdot \frac{\bar{Y}_1(K_1, L_1, E_2)}{\bar{Y}_1(K_1, L_1, E_1)} = ECOEFF \cdot TECH^2 \cdot KACC_1^2 \cdot EMIS_1^1 \\ [4] \quad \frac{Y_2}{Y_1} &= \frac{e_2}{e_1} \cdot \frac{\bar{Y}_2(K_2, L_2, E_2)}{\bar{Y}_1(K_2, L_2, E_2)} \cdot \frac{\bar{Y}_1(K_2, L_2, E_1)}{\bar{Y}_1(K_1, L_1, E_1)} \cdot \frac{\bar{Y}_1(K_2, L_2, E_2)}{\bar{Y}_1(K_2, L_2, E_1)} = ECOEFF \cdot TECH^2 \cdot KACC_1^1 \cdot EMIS_1^2 \end{aligned}$$

Multiplying the four out and taking geometrical means one obtains the expression

$$\frac{Y_2}{Y_1} = ECOEFF \cdot TECH \cdot KACC \cdot EMIS, \text{ where}$$

$$\begin{aligned} TECH &= [TECH^1 \cdot TECH^2]^{1/2} \\ KACC &= [KACC_1^1 \cdot KACC_2^1 \cdot KACC_1^2 \cdot KACC_2^2]^{1/4} \\ EMIS &= [EMIS_1^1 \cdot EMIS_2^1 \cdot EMIS_1^2 \cdot EMIS_2^2]^{1/4} \end{aligned}$$

Factors *TECH*, *KACC* a *EMIS* may be thought of as the expression of the partial effect of the technology, capital accumulation or reduction of emissions to overall eco-productivity change. The term *ECOEFF* stays constant through the four alterations and for each DMU it represents eco-efficiency change, i.e. ratio of the scores resulting from models for periods 2 and 1 being identical with the *catch-up* effect.

## 5 Results

The computation was carried out using DEA Solver by Saitech. Each of 6 models involved 29 optimizations and determining output projections. These were used to form decomposition terms described in Section 4. Potentials from the respective models are given in Table A1 in Annex. Table A2 in Annex displays terms *TECH*, *KACC*, and *EMIS* with the indexation as it appears in (2.10) – (2.11)

**Table 2** Decomposition of eco-productivity

|                | y2/y1        | e2/e1        | TECH         | KACC         | EMIS         |
|----------------|--------------|--------------|--------------|--------------|--------------|
| Belgium        | 1,269        | 1,0000       | 1,150        | 0,966        | 1,143        |
| Bulgaria       | 1,527        | 1,2101       | 1,179        | 0,992        | 1,079        |
| Czech Republic | 1,462        | 1,2164       | 1,174        | 0,944        | 1,084        |
| Denmark        | 1,185        | 1,0000       | 1,137        | 0,922        | 1,131        |
| Germany        | 1,223        | 1,0000       | 1,102        | 0,976        | 1,137        |
| Estonia        | 1,194        | 0,8733       | 1,191        | 1,211        | 0,948        |
| Ireland        | 1,448        | 1,0000       | 1,273        | 0,958        | 1,187        |
| Greece         | 1,314        | 1,0715       | 1,140        | 0,968        | 1,112        |
| Spain          | 1,310        | 0,9728       | 1,147        | 1,032        | 1,137        |
| France         | 1,207        | 1,0000       | 1,117        | 0,973        | 1,111        |
| Italy          | 1,141        | 0,9652       | 1,062        | 0,993        | 1,120        |
| Cyprus         | 1,232        | 1,1323       | 1,207        | 0,930        | 0,969        |
| Latvia         | 1,209        | 0,9206       | 1,164        | 1,155        | 0,976        |
| Lithuania      | 1,426        | 1,1002       | 1,151        | 1,084        | 1,038        |
| Hungary        | 1,388        | 1,0047       | 1,151        | 1,008        | 1,191        |
| Malta          | 1,015        | 1,0000       | 1,184        | 0,959        | 0,894        |
| Netherlands    | 1,161        | 0,9869       | 1,159        | 0,959        | 1,058        |
| Austria        | 1,107        | 0,9971       | 1,143        | 0,973        | 0,998        |
| Poland         | 1,406        | 1,1984       | 1,188        | 0,978        | 1,009        |
| Portugal       | 1,248        | 0,9026       | 1,150        | 0,997        | 1,206        |
| Romania        | 1,738        | 1,2683       | 1,173        | 0,968        | 1,208        |
| Slovenia       | 1,258        | 1,0120       | 1,158        | 1,031        | 1,041        |
| Slovakia       | 1,713        | 1,2855       | 1,148        | 1,019        | 1,139        |
| Finland        | 1,102        | 1,0618       | 1,173        | 0,920        | 0,962        |
| Sweden         | 1,289        | 1,0000       | 1,238        | 0,948        | 1,098        |
| United Kingdom | 1,352        | 1,0000       | 1,191        | 0,957        | 1,186        |
| Island         | 1,050        | 1,0000       | 1,240        | 0,948        | 0,893        |
| Norway         | 1,148        | 1,0000       | 1,158        | 0,964        | 1,029        |
| Switzerland    | 1,135        | 1,0000       | 1,187        | 0,958        | 0,998        |
| <i>priemer</i> | <i>1,285</i> | <i>1,041</i> | <i>1,167</i> | <i>0,989</i> | <i>1,072</i> |
| <i>SD</i>      | <i>0,176</i> | <i>0,105</i> | <i>0,041</i> | <i>0,065</i> | <i>0,091</i> |

Source: author's calculation

In the first column, DMUs under evaluation are listed. The second column shows change of eco-productivity, all European countries got „greener“ over time. The most pronounced improvement can be viewed in Romania and Slovakia, Iceland appears to undergo virtually no change. The other four factors help explain drivers of observed change in eco-productivity. *Catch-up* effect *ECOEFF* in the third column expresses individual effort of a country. Unit value implies that the DMU constitutes efficiency frontier in both periods. There are 11 countries with *ECOEFF* = 1, the most clear-cut improvement can be observed in case of the new EU member states (Bulgaria, Czech Republic, Slovakia, Romania). Countries Technology change *TECH* – *frontier-shift* effect in the fourth column stands for how technology change contributed to individual country's performance. This effect is clearly positive for all countries making up the

average of 1,167. *KACC* shows the effect of the change in extensive factors of production, i.e. substitution between capital and labour representing the movement along the frontier as well as the change induced by the mere reduction of emissions *ceteris paribus*. Extensive factors' contribution appears to be of no importance, it seems to have a tangible effect in developing European countries with rather high levels of capital investment (Slovenia, Slovakia, Estonia, Latvia accompanied by Spain). The effect of reduction of pollutants is at large variance in the sample with the average above the unit.

## 6 Conclusion

Concept of eco-efficiency has gained much attention and has been widely implemented in managerial and economic policy decision-making. In intertemporal setting, non-parametric approach to measuring eco-efficiency enables to decompose eco-productivity into factors attributable to changes in efficiency, technology, extensive factors of production, and emissions. Results suggest that in European countries in the span 2000 – 2010, an environment-saving rather than input-saving technology change has been taking place contributing to raising the quality of life.

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## ANNEX

**Table A1** Potential outputs for DMUs from SBM model

|                | Y2_K2_L2_E2 | Y2_K2_L2_E1 | Y2_K1_L1_E2 | Y2_K1_L1_E1 | Y1_K2_L2_E2 | Y1_K2_L2_E1 | Y1_K1_L1_E2 | Y1_K1_L1_E1 |
|----------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| Belgium        | 283267      | 246391      | 283267      | 283267      | 246391      | 246391      | 246391      | 246391      |
| Bulgaria       | 92570       | 86663       | 97770       | 97770       | 86663       | 86663       | 86663       | 75096       |
| Czech Republic | 293890      | 257102      | 309374      | 309093      | 257102      | 257102      | 257102      | 256224      |
| Denmark        | 142158      | 133759      | 161704      | 162605      | 133759      | 133759      | 133759      | 133759      |
| Germany        | 2028391     | 1840665     | 2028391     | 2028391     | 1840665     | 1840665     | 1840665     | 1840665     |
| Estonia        | 25919       | 23361       | 20332       | 20332       | 23361       | 23361       | 23361       | 15907       |
| Ireland        | 124583      | 100253      | 124583      | 124583      | 100253      | 100253      | 100253      | 95590       |
| Greece         | 286730      | 249481      | 284705      | 283899      | 249481      | 248796      | 249481      | 251114      |
| Spain          | 1024057     | 917325      | 964786      | 959387      | 917325      | 909068      | 917325      | 813861      |
| France         | 1487970     | 1332584     | 1487970     | 1487970     | 1332584     | 1332584     | 1332584     | 1332584     |
| Italy          | 1369541     | 1274741     | 1338863     | 1338863     | 1274741     | 1274741     | 1274741     | 1274741     |
| Cyprus         | 16907       | 14803       | 18489       | 18489       | 14803       | 14803       | 14803       | 14498       |
| Latvia         | 32129       | 28631       | 26219       | 25066       | 28631       | 26396       | 28631       | 20745       |
| Lithuania      | 48180       | 44529       | 43975       | 42396       | 44529       | 41523       | 44529       | 34597       |
| Hungary        | 175656      | 159887      | 173498      | 175020      | 159887      | 162026      | 159887      | 145184      |
| Malta          | 7624        | 6440        | 7624        | 7624        | 6440        | 6440        | 6440        | 6440        |
| Netherlands    | 504084      | 432217      | 506968      | 501311      | 432217      | 429203      | 432217      | 435043      |
| Austria        | 248664      | 216744      | 245827      | 242627      | 216744      | 211298      | 216744      | 213058      |
| Poland         | 518351      | 445851      | 514992      | 514992      | 445851      | 445851      | 445851      | 423940      |
| Portugal       | 187676      | 169425      | 186436      | 188888      | 169425      | 173092      | 169425      | 158174      |
| Romania        | 238235      | 213465      | 247801      | 248030      | 213465      | 213465      | 213465      | 201250      |
| Slovenia       | 50939       | 45701       | 48485       | 47562       | 45701       | 44228       | 45701       | 39514       |
| Slovakia       | 107774      | 101018      | 107711      | 107210      | 101018      | 99394       | 101018      | 86799       |
| Finland        | 139373      | 125850      | 159625      | 154842      | 125850      | 125850      | 125850      | 124682      |
| Sweden         | 266801      | 215572      | 266801      | 266801      | 215572      | 215572      | 215572      | 215572      |
| United Kingdom | 1587738     | 1333024     | 1587738     | 1587738     | 1333024     | 1333024     | 1333024     | 1333024     |
| Island         | 8743        | 7050        | 8743        | 8743        | 7050        | 7050        | 7050        | 7050        |
| Norway         | 163330      | 141051      | 163330      | 163330      | 141051      | 141051      | 141051      | 141051      |
| Switzerland    | 240940      | 203022      | 240940      | 240940      | 203022      | 203022      | 203022      | 203022      |

*Source: author's calculation*

**Table A2** Decomposition factors

|                | e2/e1 | y2 / y1 | TECH1 | TECH2 | 1KACC1 | 1KACC2 | 1EMIS1 | 1EMIS2 | 2KACC1 | 2KACC2 | 2EMIS1 | 2EMIS2 |
|----------------|-------|---------|-------|-------|--------|--------|--------|--------|--------|--------|--------|--------|
| Belgium        | 1,000 | 1,269   | 1,150 | 1,150 | 1,000  | 1,000  | 1,103  | 1,103  | 0,870  | 1,000  | 1,103  | 1,269  |
| Bulgaria       | 1,210 | 1,527   | 1,302 | 1,068 | 1,154  | 1,000  | 1,182  | 1,024  | 0,886  | 0,947  | 1,024  | 1,094  |
| Czech Republic | 1,216 | 1,462   | 1,206 | 1,143 | 1,003  | 1,000  | 1,051  | 1,048  | 0,832  | 0,950  | 1,049  | 1,197  |
| Denmark        | 1,000 | 1,185   | 1,216 | 1,063 | 1,000  | 1,000  | 1,115  | 1,115  | 0,823  | 0,879  | 1,109  | 1,185  |
| Germany        | 1,000 | 1,223   | 1,102 | 1,102 | 1,000  | 1,000  | 1,109  | 1,109  | 0,907  | 1,000  | 1,109  | 1,223  |
| Estonia        | 0,873 | 1,194   | 1,278 | 1,109 | 1,469  | 1,000  | 1,233  | 0,839  | 1,149  | 1,275  | 0,839  | 0,931  |
| Ireland        | 1,000 | 1,448   | 1,303 | 1,243 | 1,049  | 1,000  | 1,165  | 1,111  | 0,805  | 1,000  | 1,111  | 1,380  |
| Greece         | 1,071 | 1,314   | 1,131 | 1,149 | 0,991  | 1,000  | 1,067  | 1,077  | 0,879  | 1,007  | 1,077  | 1,234  |
| Spain          | 0,973 | 1,310   | 1,179 | 1,116 | 1,117  | 1,000  | 1,206  | 1,080  | 0,956  | 1,061  | 1,076  | 1,195  |
| France         | 1,000 | 1,207   | 1,117 | 1,117 | 1,000  | 1,000  | 1,081  | 1,081  | 0,896  | 1,000  | 1,081  | 1,207  |
| Italy          | 0,965 | 1,141   | 1,050 | 1,074 | 1,000  | 1,000  | 1,100  | 1,100  | 0,952  | 1,023  | 1,100  | 1,182  |
| Cyprus         | 1,132 | 1,232   | 1,275 | 1,142 | 1,021  | 1,000  | 0,952  | 0,933  | 0,801  | 0,914  | 0,933  | 1,065  |
| Latvia         | 0,921 | 1,209   | 1,208 | 1,122 | 1,272  | 1,000  | 1,170  | 0,919  | 1,142  | 1,225  | 0,887  | 0,951  |
| Lithuania      | 1,100 | 1,426   | 1,225 | 1,082 | 1,200  | 1,000  | 1,198  | 0,998  | 1,050  | 1,096  | 0,965  | 1,007  |
| Hungary        | 1,005 | 1,388   | 1,206 | 1,099 | 1,116  | 1,000  | 1,257  | 1,127  | 0,914  | 1,012  | 1,132  | 1,254  |
| Malta          | 1,000 | 1,015   | 1,184 | 1,184 | 1,000  | 1,000  | 0,857  | 0,857  | 0,845  | 1,000  | 0,857  | 1,015  |
| Netherlands    | 0,987 | 1,161   | 1,152 | 1,166 | 0,987  | 1,000  | 1,008  | 1,022  | 0,862  | 0,994  | 1,026  | 1,184  |
| Austria        | 0,997 | 1,107   | 1,139 | 1,147 | 0,992  | 1,000  | 0,968  | 0,976  | 0,893  | 1,012  | 0,964  | 1,091  |
| Poland         | 1,198 | 1,406   | 1,215 | 1,163 | 1,052  | 1,000  | 1,009  | 0,960  | 0,866  | 1,007  | 0,960  | 1,116  |
| Portugal       | 0,903 | 1,248   | 1,194 | 1,108 | 1,094  | 1,000  | 1,249  | 1,141  | 0,897  | 1,007  | 1,151  | 1,291  |
| Romania        | 1,268 | 1,738   | 1,232 | 1,116 | 1,061  | 1,000  | 1,228  | 1,158  | 0,861  | 0,961  | 1,157  | 1,292  |
| Slovenia       | 1,012 | 1,258   | 1,204 | 1,115 | 1,119  | 1,000  | 1,115  | 0,996  | 0,961  | 1,051  | 0,983  | 1,075  |
| Slovakia       | 1,285 | 1,713   | 1,235 | 1,067 | 1,145  | 1,000  | 1,249  | 1,091  | 0,942  | 1,001  | 1,078  | 1,145  |
| Finland        | 1,062 | 1,102   | 1,242 | 1,107 | 1,009  | 1,000  | 0,937  | 0,929  | 0,813  | 0,873  | 0,957  | 1,028  |
| Sweden         | 1,000 | 1,289   | 1,238 | 1,238 | 1,000  | 1,000  | 1,041  | 1,041  | 0,808  | 1,000  | 1,041  | 1,289  |
| United Kingdom | 1,000 | 1,352   | 1,191 | 1,191 | 1,000  | 1,000  | 1,135  | 1,135  | 0,840  | 1,000  | 1,135  | 1,352  |
| Island         | 1,000 | 1,050   | 1,240 | 1,240 | 1,000  | 1,000  | 0,847  | 0,847  | 0,806  | 1,000  | 0,847  | 1,050  |
| Norway         | 1,000 | 1,148   | 1,158 | 1,158 | 1,000  | 1,000  | 0,992  | 0,992  | 0,864  | 1,000  | 0,992  | 1,148  |
| Switzerland    | 1,000 | 1,135   | 1,187 | 1,187 | 1,000  | 1,000  | 0,956  | 0,956  | 0,843  | 1,000  | 0,956  | 1,135  |

*Source: author's calculation*