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Eco-Efficiency Measurement by Implementing DEA Models with Weight Restrictions

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Abstract. Nowadays, there is consensus on the fact that the sustainability, in which the international political debate constitute one of the most powerful concepts, opens entirely new opportunities for reaching higher levels of development. Sustainability development means making sure the social, economic and environmental needs of current generations are met and kept healthy for future generations. Increasing importance of sustainable development has lead eco-efficiency to find a specific position in literature. Efficiency is an index that measures management ability in optimal use of inputs for generating outputs. A unit can be more efficient if it produces 1) the same outputs with fewer inputs 2) more or better outputs for the same inputs. Data Envelopment Analysis (DEA) is one of the power efficient evaluation methods. In this paper, a new method is proposed for appraising eco-efficiency of manufacturing factories based on an extended DEA approach. The advantage of this model in contrast with current models in eco-efficiency is that DM can keep in perfect control the dispersal of weights. Finally, a case study is implemented by using simulated data in order to evaluate proposed model.

Keywords: Sustainability Development, Eco-efficiency Measurement, Data Envelopment Analysis, DEA, Weight Restrictions, Desirable Outputs, Undesirable Outputs.

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1 Introduction

Nowadays, sustainability is one of the most significantly challenging concepts in the global political debate. Sustainable development was articulated by the Brundtland Commission as development that "meets the needs of the present without compromising the ability of future generations to meet their own needs".

Sustainable development must consider economic, environmental and social considerations, simultaneously. These issues illustrate the importance of disciplines as diverse as ecology, economics and sociology in developing a sustainable development perspective [2]. In fact, moving toward sustainable development needs to meet the objectives in three mentioned areas in such a way that [1]:

- Maintain a high and stable level of economical growth and employment.
- Effective protection of the environment.
- Provide social progress which recognizes the needs of every one.

Linking environmental and economic performance, eco-efficiency is primarily a management concept. Eco-efficiency differs from sustainability in that eco-efficiency does not measure social aspects. The WBCSD defines eco-efficiency as[3]: Eco-efficiency = Product or service value / Environmental influence.

This concept measures by using different indexes. Most of the time, because of lack information related to ecological indexes, we cannot precisely calculate eco-efficiency in industries. For instance, because of having no information about market prices for the undesirable outputs, we are not able to estimate the environmental costs. Using DEA helps us to overcome these kinds of difficulties in measuring eco-efficiency. In order to ecological decision makings, top managements of firms need to a method for evaluating eco-efficiency of their products processes. For this purpose, in last years, researchers have studied different methods for measuring eco-efficiency based on DEA in various case studies. Some of these case studies have mentioned in table 1.

Table 1 Eco-efficiency Case studies by using DEA

Case study	Author	Year
Paper mills along the Huai River	Feng Yang et al.[6]	2011
Electric and Electronic Appliances Factories	Barba-Gutiérrez et al.[7]	2009
Industries Systems in China	Bing Zhang et al.[5]	2008
Paper mills along the Huai River	Zhongsheng Hua et al.[8]	2007
Valuing environmental factors in cost-benefit analysis	Kuosmanen, Kortelainenb[9]	2007
Furniture production industry of Norwegian	Ottar Michelsen[10]	2006
Electric power plants in Europe	Korhonen et al.[11]	2004

2 A Literature Review on Eco-efficiency Measurement

Some contributions are found in literature, indicating the applicability of the approaches of DEA to sustainability and eco-efficiency [5-12]. To evaluate eco-efficiency, each of plants is considered as a decision making unit (DMU) that has inputs and outputs. Assume we have two kinds of outputs (desirable output and undesirable output) and n DMUs each consuming m inputs and producing p outputs. The outputs corresponding to indexes $1,2,...,k$ are desirable and the outputs corresponding to indexes $k+1,k+2,...,p$ are undesirable outputs. We like to produce desirable outputs as much as possible and not to produce undesirable outputs.

Let $X \in R^{m\times n}$ and $Y \in R^{p\times n}$ be the matrices, consisting of non-negative elements, containing the observed input and output measures for the DMUs. We decompose matrix Y into two parts: $Y = \begin{pmatrix} Y^g \\ Y^b \end{pmatrix}$

Where a $k \times n$ matrix Y^g is standing for desirable outputs and a $(p-k)\times n$ matrix Y^b is standing for undesirable outputs. We further assume that there are no duplicated units in the data set. We denote by x_j (the j^{th} column of X) the vector of inputs consumed by DMU_j, and by x_{ij} the quantity of input i consumed by DMU_j. A similar notation is used for outputs. Occasionally, we decompose the vector y_j into two parts: $y_j = \begin{pmatrix} y_j^g \\ y_j^b \end{pmatrix}$

Where the vectors y_j^g and y_j^b refers to the desirable and undesirable output-values of unit j. We denote vector u as following: $u = \begin{pmatrix} y^g \\ -y^b \\ -x \end{pmatrix}$ $U = \begin{pmatrix} Y^g \\ -Y^b \\ -X \end{pmatrix}$

In this notation, inputs and desirable, undesirable outputs are assumed as vector that inputs and undesirable output appear with negative sign.

Korhonen and Luptacik [11] presented models for evaluating eco-efficiency based on DEA. Two kinds of efficiency are defined for evaluating eco-efficiency: 1) Technical efficiency 2) Ecological efficiency.

Model 1: The DEA traditional model proposed by Charnes et al. [12] is used for measuring the technical efficiency.

$$Max \quad h_0 = \frac{\sum_{r=1}^{k} \mu_r y_{r0}}{\sum_{i=1}^{m} v_i x_{i0}}$$

$$s.t. \ \frac{\sum_{r=1}^{k} \mu_r y_{rj}}{\sum_{i=1}^{m} v_i x_{ij}} \leqslant 1, \quad j = 1,2,...,n \qquad \mu_r, v_i \geqslant \varepsilon, \ r = 1,2,...,k;\ i = 1,2,...,m,\ \ \varepsilon > 0(\text{"Non Archimedean"}).$$

In this model, each of DMU has a set of inputs and outputs. Also, outputs are not decomposed i.e. desirable and undesirable outputs are considered together.

Model 2: The following model is designed for evaluating ecological efficiency. In this model, outputs are just used i.e. for each of DMU, undesirable outputs are considered as inputs and desirable outputs are considered as DMU outputs and similarly the DEA classical model is solved.

$$Max \quad g_0 = \frac{\sum_{r=1}^{k} \mu_r y_{r0}}{\sum_{s=k+1}^{p} \mu_s y_{s0}}$$

$$s.t. \ \frac{\sum_{r=1}^{k} \mu_r y_{rj}}{\sum_{s=k+1}^{p} \mu_s y_{sj}} \leqslant 1, \quad j = 1,2,\ldots,n, \qquad \mu_r \geqslant \varepsilon, \ r = 1,\ldots,p, \qquad \varepsilon > 0(\text{" Non Archimedea n" }).$$

Model A: In this model, we build up the desirable and undesirable outputs simultaneously. This model takes into account linear combination of outputs (as a weighted sum), using negative weights for undesirable outputs i.e. the model takes into account pure output.

$$Max \quad g_0 = \frac{\sum_{r=1}^{k} \mu_r y_{r0} - \sum_{s=k+1}^{p} \mu_s y_{s0}}{\sum_{i=1}^{m} v_i x_{i0}}$$

$$s.t. \ \frac{\sum_{r=1}^{k} \mu_r y_{rj} - \sum_{s=k+1}^{p} \mu_s y_{sj}}{\sum_{i=1}^{m} v_i x_{ij}} \leqslant 1$$

$$j = 1,2,\ldots,n, \ \ \mu_r, v_i \geqslant \varepsilon, \ \ r = 1,\ldots,p, \qquad i = 1,2,\ldots,m, \ \ \varepsilon > 0(\text{" Non Archimedea n" })$$

Model B: In this model, the undesirable outputs are taken into account as inputs and the desirable outputs are considered as outputs.

$$Max \quad g_0 = \frac{\sum_{r=1}^{k} \mu_r y_{r0}}{\sum_{i=1}^{m} v_i x_{i0} + \sum_{s=k+1}^{p} \mu_s y_{s0}}$$

$$s.t. \ \frac{\sum_{r=1}^{k} \mu_r y_{rj}}{\sum_{i=1}^{m} v_i x_{ij} + \sum_{s=k+1}^{p} \mu_s y_{sj}} \leqslant 1$$

$$j = 1,2,\ldots,n, \ \mu_r, v_i \geqslant \varepsilon, \ r = 1,\ldots,p, \quad i = 1,2,\ldots,m, \ \varepsilon > 0(\text{" Non Archimedea n" }).$$

Model C: In this model, the undesirable outputs are taken into account as inputs and the inputs are taken into account as undesirable outputs i.e. the inputs and the undesirable outputs are considered as output.

$$Max\ g_0 = \frac{\sum_{r=1}^{k}\mu_r y_{r0} - \sum_{i=1}^{m} v_i x_{i0}}{\sum_{s=k+1}^{p}\mu_s y_{s0}}$$

$$s.t.\ \frac{\sum_{r=1}^{k}\mu_r y_{rj} - \sum_{i=1}^{m} v_i x_{ij}}{\sum_{s=k+1}^{p}\mu_s y_{sj}} \leqslant 1, \quad j=1,2,\ldots,n,\ \mu_r, v_i \geqslant \varepsilon,\ r=1,\ldots,p, \quad i=1,2,\ldots,m,\ \varepsilon>0(\text{"Non Archimedean"}).$$

Model D: In this model, the undesirable outputs are taken into account as inputs and the inputs are taken into account as undesirable output i.e. the inputs and the undesirable outputs are considered as output and the desirable output are considered as input.

$$Min\ h_D = \frac{\sum_{s=k+1}^{p}\mu_s y_{s0} + \sum_{i=1}^{m} v_i x_{i0}}{\sum_{r=1}^{k}\mu_r y_{r0}}$$

$$s.t.\ \frac{\sum_{s=k+1}^{p}\mu_s y_{sj} + \sum_{i=1}^{m} v_i x_{ij}}{\sum_{r=1}^{k}\mu_r y_{rj}} \leqslant 1 \quad j=1,2,\ldots,n,\ \mu_r, v_i \geqslant \varepsilon,\ r=1,\ldots,p, \quad i=1,2,\ldots,m,\ \varepsilon>0(\text{"Non Archimedean"}).$$

3 A New Approach for Eco-Efficiency Measurement

Our proposed method for eco-efficiency analysis is described as follows. First of all, the traditional models of eco-efficiency are solved. The results show that some of input or output variables (weights) tend to zero. This means that we ignore the importance of some measure in evaluating eco-efficiency. In this paper, we want to resolve this weakness of the DEA traditional model. In order to overcome this problem, we apply Weight Restriction in DEA models to keep in control the dispersal of input and output's weights i.e. upper limit and lower limit on each of the weights are adopted by DM. The weight restrictions attach to the DEA models for considering the importance of all measures. This means that the coefficients of inputs and outputs do not tend to zero. Weight Restrictions Model overcomes this problem that in similar works, this model have not considered for evaluating Eco-efficiency. The weight restrictions attach to the DEA model as follows:

$$\begin{aligned} a_r \leqslant U_r \leqslant b_r \\ c_i \leqslant V_r \leqslant d_i \end{aligned} \qquad (U_r, V_r \neq 0)$$

Now, we study the problem of the traditional models for measuring eco-efficiency and observe that it is resolved. After solving the models with the DEA traditional method, the results show that some of weights (u,v in some DMUs) tend to zero and This means to ignore the importance of that measure in evaluating that DMU.

In order to overcome this problem and interact with DM's ideas for determining the DEA weights, weight restriction method is applied to keep in control the dispersal of input and output's weights. In order to solve this problem, the weight restrictions impose to the model with doing changes as follows:

$$Q_r^1 \leqslant \mu_r \leqslant Q_r^2,\ \forall r = 1,\dots, s \Rightarrow \begin{array}{l} Q_1^1 \leqslant \mu_1 \leqslant Q_1^2 \\ Q_2^1 \leqslant \mu_2 \leqslant Q_2^2 \\ \vdots \\ Q_s^1 \leqslant \mu_r \leqslant Q_s^2 \end{array}$$

Q_r^1 : Lower limit of r[th] output index
Q_r^2 : Upper limit of r[th] input index

$$P_i^1 \leqslant v_i \leqslant P_i^2,\ \forall i = 1,\dots, m \Rightarrow \begin{array}{l} P_1^1 \leqslant v_1 \leqslant P_1^2 \\ P_2^1 \leqslant v_2 \leqslant P_2^2 \\ \vdots \\ P_m^1 \leqslant v_m \leqslant P_m^2 \end{array}$$

P_i^1 : Lower limit of r[th] output index
P_i^2 : Upper limit of r[th] input index

These are decided by DMs. Now, these weights are normalized and then added to the model as linear.

$$\forall r_1, r_2 \in \{1,\dots, s\} : \frac{\mu_{r1}}{\mu_{r2}} \leqslant \frac{Q_{r1}^2}{Q_{r2}^1},\ \frac{\mu_{r1}}{\mu_{r2}} \geqslant \frac{Q_{r1}^1}{Q_{r2}^2}$$

$$\forall r_1, r_2 \in \{1,\dots, s\} : \frac{\mu_{r1}}{\mu_{r2}} \leqslant \frac{Q_{r1}^2}{Q_{r2}^1},\ \frac{\mu_{r1}}{\mu_{r2}} \geqslant \frac{Q_{r1}^1}{Q_{r2}^2}$$

$$Q_{r2}^1\,\mu_{r1} - Q_{r1}^2\,\mu_{r2} \leqslant 0,$$
$$Q_{r1}^1\,\mu_{r2} - Q_{r2}^2\,\mu_{r1} \leqslant 0.$$

Equivalently for v_i : $P_{i2}^1\,v_{i1} - P_{i1}^2\,v_{i2} \leqslant 0$,
$Q_{i1}^1\,v_{i2} - Q_{i2}^2\,v_{i1} \leqslant 0$.

The Output oriented model of DEA is calculated after imposing the weight restrictions as follows:

$$Max\ h_0 = \frac{\sum_{r=1}^{k} \mu_r y_{r0}}{\sum_{i=1}^{m} v_i x_{i0}}$$

$$s.t.\ \frac{\sum_{r=1}^{k} \mu_r y_{rj}}{\sum_{i=1}^{m} v_i x_{ij}} \leq 1,\quad j = 1,2,\dots,n$$

$$Q_{r2}^1\,\mu_{r1} - Q_{r1}^2\,\mu_{r2} \leq 0,\ for\ all\ combination\ r_1, r_2 \in \{1,2,\dots m\}, r_1 < r_2$$
$$Q_{r1}^1\,\mu_{r2} - Q_{r2}^2\,\mu_{r1} \leq 0$$
$$P_{i2}^1\,v_{i1} - P_{i1}^2\,v_{i2} \leq 0,\ for\ all\ combination\ i_1, i_2 \in \{1,2,\dots m\}, i_1 < i_2$$
$$Q_{i1}^1\,v_{i2} - Q_{i2}^2\,v_{i1} \leq 0$$
$$\mu_r, v_i \geq \varepsilon,\ r = 1,2,\dots k;\ i = 1,2,\dots m,$$
$$\varepsilon > 0(\text{"Non Archimedean"}).$$

The lined model is as follows:

$$Max\ \ h_0 = \sum_{r=1}^{k} \mu_r y_{r0}$$

$$s.t.\ \ \sum_{i=1}^{m} v_i x_{i0} = 1$$

$$\sum_{r=1}^{k} \mu_r y_{rj} \qquad \sum_{i=1}^{m} v_i x_{ij} \leqslant 0, \quad j = 1,2,\ldots, n$$

$$\begin{aligned}
&Q_{r2}^{1}\ \mu_{r1} - Q_{r1}^{2}\ \mu_{r2} \leqslant 0,\ \ for\ \ all\ \ combination\ \ r_1, r_2 \in \{1,2,\ldots,m\}, r_1 < r_2\\
&Q_{r1}^{1}\ \mu_{r2} - Q_{r2}^{2}\ \mu_{r1} \leqslant 0\\
&P_{i2}^{1}\ v_{i1} - P_{i1}^{2}\ v_{i2} \leqslant 0,\ \ for\ \ all\ \ combination\ \ i_1, i_2 \in \{1,2,\ldots,m\}, i_1 < i_2\\
&Q_{i1}^{1}\ v_{i2} - Q_{i2}^{2}\ v_{i1} \leqslant 0\\
&\mu_r, v_i \geqslant \varepsilon,\ \ r = 1,2,\ldots,k;\ i = 1,2,\ldots,m,\\
&\varepsilon > 0(\text{"Non} \quad \text{Archimedean"}).
\end{aligned}$$

The advantage of this model in contrast with current models in eco-efficiency is that DM can keep in perfect control the dispersal of weights. In the next section, in order to evaluate the proposed model, a case study is implemented by using simulated data.

4 An Illustrative Case Study: Electric Power Plant

This case study includes 12 production units of an electric power plant that have been investigated during a period of 3-year performance. There are two input indexes and three output indexes (one desirable index and two undesirable indexes) as following table 2:

Table 2 Input and output indexes of power plants

Inputs	Outputs
1.Actual total cost 2.Pollutions reduction investment	3.NO_x pollution 4. SO_2 pollution 5.Electricity production volume

Information of above indexes in 12 power plants has been gathered. Indexes information has been normalized because of preventing from numerical and computational errors of model solving software, so that the value of each index has been divided on the maximum value of same index. Then the obtained values have been changed to the values into interval of [0,100] after multiplying in 100.

At first, the CCR model with output navigate has been solved without imposing weight restrictions on the data. Efficiency resulted of power plants and calculated weights of indexes related to each power plant have been derived from the model. Regarding to these numbers, we see that some of these weights tend to zero. Information of inputs and outputs indexes as follows:

Table 3 The input and output indexes

	The input indexes (X)		The output indexes (Y)		
	1	2	3	4	5
1	88.83303	100	62.12292	69.37775	97.76303
2	54.6848	52.17492	85.16222	88.76824	93.38699
3	51.30735	79.04572	59.729	94.86904	100
4	100	89.99282	89.80189	66.25553	60.25132
5	70.15584	75.20597	52.40895	90.29915	87.55983
6	51.21231	89.1723	94.65415	90.04405	93.17322
7	95.62056	46.36668	100	53.08573	78.83214
8	64.22097	46.75135	70.55387	81.92634	74.57346
9	57.91213	49.83428	78.54623	79.77603	59.78789
10	43.20474	53.75819	89.6406	100	95.5791
11	94.89299	71.29924	62.99006	64.534	87.31951
12	67.40328	61.42263	98.10595	75.68851	96.16712

Results of eco-efficiency obtained from solving the classical DEA model 1 without imposing the weights restrictions have been shown as following table:

Table 4 The Results of eco-efficiency for classical model 1 without weights restrictions

Plant	1	2	3	4	5	6	7	8	9	10	11	12
Eco-efficiency	54.8	100	88.1	55.8	65.4	89.0	100	94.2	90.8	100	68.4	89.6

Table 5 The weights Resulted of solving classical model 1 without weights restrictions

	AU		AV		
	1	2	3	4	5
1	0.0004996	0.0177848	0	0	0.0102288
2	0.000523	0.0186181	0	0	0.0107081
3	0.0221224	0	0	0	0.01
4	0.0043287	0.0150895	0.0111356	0	0
5	0	0.0203267	0	0.0007967	0.0105992
6	0.0219197	0	0.0105648	0	0
7	0.0038873	0.0135506	0.01	0	0
8	0	0.0227055	0	0.0122061	0
9	0	0.0220853	0.0075124	0.0051385	0
10	0.0231456	0	0	0	0.0104625
11	0	0.0204981	0	0	0.0114522
12	0.0039623	0.0138123	0.0101931	0	0

It's observed that some weights tend to zero. Then, the CCR model with output navigate has been solved with imposing weight restrictions that have been derived from DM's ideas. DM's ideas have been added to the model as a weighted interval that power plants indexes weight will not exceed from this interval. Efficiency results and calculated weights of indexes on each of the power plants have been derived from the model. What we see in the results, no weights tend to zero. The weighted intervals have been considered by DM as follows:

$40 \le V_1 \le 60$ $\quad 40 \leqslant U_1 \leqslant 60$

$30 \le V_2 \le 45$ $\quad 25 \leqslant U_2 \leqslant 35$

$15 \leqslant U_3 \leqslant 25$

These weighted intervals have been changed to polynomial expressions according to presented pattern. Results of eco-efficiency obtained from solving the DEA model 1 with imposing the weights restrictions have been shown as follow:

Table 6 Results of eco-efficiency for model 1 with weights restrictions

Plant	1	2	3	4	5	6	7	8	9	10	11	12
Eco-efficiency	40.4	86.0	66.8	43.9	52.6	73.2	64.1	70.9	74.2	100	44.1	75.3

Table 7 The weights Resulted of solving model 1 with weights restrictions

	AU		AV		
	1	2	3	4	5
1	0.0122671	0.0138004	0.0060029	0.0037518	0.0037518
2	0.0102479	0.0115289	0.0062089	0.002587	0.002587
3	0.0164682	0.0082341	0.0048724	0.0042633	0.0030452
4	0.0112998	0.0127122	0.0075488	0.0031453	0.0018872
5	0.0122734	0.0138076	0.0053721	0.0047006	0.0033576
6	0.0142444	0.0071222	0.0064323	0.0026801	0.0016081
7	0.0105544	0.0118737	0.0070508	0.0029378	0.0017627
8	0.0120689	0.0135775	0.0058753	0.0051409	0.0022032
9	0.0118114	0.0132878	0.0078906	0.0032877	0.0019726
10	0.0142686	0.0071343	0.0046952	0.0041083	0.0017607
11	0.012942	0.0145597	0.0063332	0.0039582	0.0039582
12	0.0097255	0.0109412	0.0058923	0.0024551	0.0024551

It's observed that with imposing the weight restrictions to the model, no weights tend to zero. The proposed approach was examined for other DEA models of eco-efficiency measurement (i.e. A, B, C, D) and the same story has happened to them. No weights tend to zero by imposing the weight restrictions to the model. That means DM can keep in perfect control the dispersal of weights.

5 Conclusion

Efficiency is an index that measures management ability of decision maker unit in optimal use of the inputs for producing the outputs. A unit is more efficient if it's able to generate more output with respect to lower level of input. This paper conducted an eco-efficiency analysis for manufacturing factories based on an extended Data Envelopment Analysis approach. We examined the role that weight restrictions play in DEA. The result showed that the decision to include a factor (input or output) in a DEA model represents an implicit judgment that the factor has a non-trivial weight. It therefore seemed perverse to allow DEA to assign a trivial weight to that factor in assessing the efficiency of a unit. Hence there was a strong case for imposing restrictions on factor weights. The advantage of this model in contrast with current models in eco-efficiency is that DM can keep in perfect control the dispersal of weights. For the future work, the proposed model can be implemented for evaluating eco-efficiency in an actual case study.

Reference

1. Dehghanian, F., Mansour, M.: Designing sustainable recovery network of end-of-life products using genetic algorithm, Resources. Conservation and Recycling 53, 559–570 (2009)
2. Cowell, S., Parkinson, S.: Localisation of UK food production: an analysis using land area and energy as indicators. Agriculture, Ecosystems and Environment 94, 221–236 (2003)
3. WCED (World Commission on Environment and Development) our common future. Oxford University Press, Oxford (1987)
4. Fathi, M., et al.: Using Compromised Method in Design of Reverse Logistics Network with Eco-Efficiency Consideration. IEEE Transactions on Industrial Engineering, 1454–1458 (2009)
5. Zhang, B., et al.: Eco-efficiency analysis of industrial system in China: A data envelop-ment analysis approach. Ecological Economics 68, 306–316 (2008)
6. Yang, F., et al.: Modeling undesirable outputs in eco-efficiency evaluation to paper mills along the Huai River based on DEA. Environment and Sustainable Development 10, 36–47 (2011)
7. Barba-Gutiérrez, Y., et al.: Eco-Efficiency of Electric and Electronic appliances: A Data Envelopment Analysis. Environmental Modeling and Assessment 14, 439–447 (2009)
8. Hua, Z., et al.: Eco-efficiency analysis of paper mills along the Huai River: An extended DEA approach. Omega 35, 578–587 (2007)
9. Kuosmanen, T., Kortelainen, M.: Valuing environmental factors in cost–benefit analysis using data envelopment analysis. Ecological Economics 62, 56–65 (2007)
10. Michelsen, O.: Eco-efficiency in redesigned extended supply chains; furniture as an example. Eco-Efficiency in Industry and Science 22, 163–179 (2007)
11. Korhonen, P.J., Luptacik, M.: Eco-efficiency analysis of power plants: An extension of data envelopment analysis. Eur. J. Operational Research 154, 437–446 (2004)
12. Charnes, A., Cooper, W., et al.: Short communication: Measuring efficiency of decision making units. Eur. J. Operational Research 3, 339 (1979)