OR-based Eco-efficiency Measuring for Economic-ecological Trade-offs Analysis

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Abstract: Traditional eco-efficiency measurements insufficiently support trade-offs analysis. The objective of the paper is to explore trade-offs analysis support from the branch of productive efficiency analysis techniques. The paper focuses on the linear programming based data envelopment analysis (DEA) models, adjusted for an analogous treatment of the economic and environmental outcomes. In particular, the models are adjusted for the materials balance principle. They allow for differentiating between win-win and trade-offs while substituting for inputs or outputs. Their results are obvious for simple production processes, but the message gets blurred with multiple inputs, outputs and outcomes. The paper explores multiple economic-ecological trade-offs with materials-balance-based efficiency DEA models with a simple illustrative case of 62 typical pig firms. Separate DEA models calculate technical, economic and the efficiency for nutrient, water and energy use. Mutual win-wins and trade-offs are shown. Shortcomings are discussed and further model adjustments based on directional distance functions, instead of radial ones, are proposed.

1 INTRODUCTION

Eco-efficiency indicators integrate economic and ecological values in a ratio key figure (Dahlström and Ekins, 2005) and compare performances on a discrete basis. They fail to derive more continuous management information on how an outcome, e.g. the economic one, evolves when trying to improve another, e.g. the environmental one. One solution is to consider the underlying production process, and to analyse drivers for both economic and environmental outcomes. The production process is a physical transformation of inputs into outputs (Coelli et al., 2005). As such, it contains no economic or ecological value, unless more information is provided. Prices are necessary to derive costs, revenues and profit. When linking production data with materials balance information also ecological values can be derived (Coelli et al., 2007); (Lauwers, 2009).

Huppes and Ishikawa (2005) and Kuosmanen and Kortelainen (2005) show how eco-efficiency can be measured with frontier models. Reviews of environmentally adjusted frontier models are given by Tyteca (1996), Scheel (2001) and Lauwers (2009). Two types exist: parametric stochastic and non-parametric data envelopment analysis (DEA) models. The first draws a functional form enveloping a set of observed data, the second envelops data with a piece-wise linear frontier. In this paper, we concentrate on the non-parametric methods, based on linear programming. An on-going discussion in literature is how to incorporate the environmental outcome in the production model and to derive eco-efficiency. This paper will shortly summarize this state-of-the-art in order to allow the reader to get pace with the modelling challenges.

The objective of the paper is to explore multiple economic-ecological trade-offs with materials-balance-based efficiency DEA models. Trade-offs are illustrated with one economic, profit, and three environmental outcomes from a simple illustrative case of 62 typical pig finishing firms. Besides DEA models for calculating technical efficiency and economic efficiency, similar models are conceived for calculating the efficiency for nutrient, water and energy use. This allows to derive their mutual win-wins and trade-offs. Shortcomings are discussed and further model adjustments are proposed.

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2 MODELS OF PRODUCTIVE EFFICIENCY ANALYSIS

This section shortly describes, first, how productive and eco-efficiency differ, but to a certain extent are interlinked and, second, how these differences and similarities can appropriately be modelled.

2.1 Productive and Eco-efficiency

Firms differ in efficiency to transform inputs into outputs. For measuring a firm's efficiency, frontier functions are used. Frontier functions represent the efficient transformation, this is no other firm can be found that use less input for the same output, or generates more output with the same input. The distance of a firm's input-output configuration to the frontier is a measure for technical efficiency.

When price information is added to the physical input-output transformation, economic outcomes such as profit can be derived. More, the optimal input-output combinations that maximise profit can be searched. The concept of optimal combination of input is measured as allocative efficiency.

The production process has various outcomes. We consider an outcome as issuing from the net utility or disutility of the set of outputs, corrected for the sacrifices that had been put into the transformation. As such, outcome is distinguished from the mere physical output. When prices of inputs (P_{Xi}) and output (P_{Yj}) are known, economic margin (Π), e.g. profit, can be calculated as:

$$\Pi = \sum P_{Yj} * Y_j - \sum P_{Xi} * X_i \quad (1)$$

The pressure a firm exerts on the environment is another outcome, e.g. the nitrogen balance is an indicator for disutility from by-products resulting from pig finishing. When nitrogen contents of inputs (N_{Xi}) and output (N_{Yj}) are known, the balance (B) can be calculated similar to the economic margin:

$$B = N_{Xi} * X_i - \sum N_{Yj} * Y_j \quad (2)$$

Eco-efficiency measures how much profit is obtained over the (potential) environmental burden:

$$\Pi / B \quad (3)$$

2.2 Data Envelopment Models

Technical efficiency, TE, (θ) can be measured with a linear programming model drawing a piece-wise linear envelop around the data set. The general form is described by the formula (4) – (7). For each farm i, with (x_i, y_i) as input –output configuration, another LP and efficiency score (θ) is obtained. Each solution also gives a vector of weight λ that determines the envelop, or production frontier. This technique of deriving the frontier and a TE score is called DEA, data envelopment analysis. Technical inefficiency, as the distance from the actual (x_i , y_i) to the frontier, can be measured in various way, the model (4)-(7) measures TE from a radial input – minimising perspective:

$$\min_{\theta,\lambda} \quad \Theta \quad (4)$$
$$\text{s.t.} \quad -y_i + Y\lambda \geq 0 \quad (5)$$
$$\theta x_i - X\lambda \geq 0 \quad (6)$$
$$\lambda \geq 0 \quad (7)$$

with:

- (x_i , y_i) the input –output of farm i;
- Y is the output matrix of all n firms;
- X is the input matrix of all n firms;
- λ is a scalar of weights.

With price information p_i, economic efficiency scores can be measured from similar models. The model (8)-(11) results in a cost-minimising vector $x°_i$ for each firm i:

$$\min_{\lambda,\, x°_i} \quad p_i\, x°_i \quad (8)$$
$$\text{s.t.} \quad -y_i + Y\lambda \geq 0 \quad (9)$$
$$x°_i - X\lambda \geq 0 \quad (10)$$
$$\lambda \geq 0 \quad (11)$$

with:

- (x_i , y_i) the input –output of farm i;
- Y is the output matrix of all n firms;
- X is the input matrix of all n firms;
- λ is a scalar of weights;
- p_i is the vector of input prices

The economic efficiency CE is then calculated from the observed cost-minimizing vector and the overall optimum, OO (12), which then can be decomposed in a technical, TE, and an allocative efficiency, CAE, component (13).

$$CE = p_i\, x°_i / OO \quad (12)$$
$$CAE = CE / TE \quad (13)$$

We build similar models with the resource use coefficients n_i, w_i, and e_i instead of the prices p_i, and search for the resource use minimizing vector. Similar to (12), nitrogen (NE), water (WE) and energy (EE) use efficiency can be calculated. As TE remains the same over the four efficiency measurements, the various environmental efficiency scores then leads to nitrogen use allocative efficiency (NAE), water use allocative efficiency (WAE) and energy use allocative (EAE) score.

Scores estimate improvement potentials. TE scores show the physical improvement margin, which will not differ across the various outcome-optimisation models. Regardless whether we want to minimise cost or resources use, a radial contraction of inputs will proportionally save on both objectives. The interpretation of AE concerns the substitution of inputs and provides a differentiated picture of trade-offs.

3 RESULTS

3.1 The Pig-finishing Case

The pig-finishing process is used as a case with kg marketable pig as desired output and feed and piglets as the main variable inputs. In the short run, the number of pig places (capital input) and labour can be considered as fixed. The finishing activity starts with a piglet of 23 kg and ending with a hog of about 113 kg. This takes about 140 days, thus each pig place can be occupied by more than one piglet per year to finish as a marketable pig. A set of 62 typical farms are drawn from an original data panel of about 300 farms over 3 bookkeeping years (2007-2009). Summarizing statistics are given in table 1.

Table 1: Statistics of the data set of 62 typical farms.

Feature	Mean	Minimum	Maximum
Y, tonnes marketable pig /year	262	56	771
Pig price, euro/kg	1.12	0.96	1.20
Nitrogen content pig, kg/kg	0.026	0.026	0.026
Feed input, kg/year	633	143	1944
Feed price, euro/kg	0.23	0.17	0.26
Nitrogen content feed,	0.025	0.025	0.025
Water use, liter per kg	1.59	1.06	2.22
Energy use, MJoule/kg	3.40	3.40	3.40
Number of piglets per year	2467	484	6216
Price per piglet	40	31	52
Nitrogen content, kg/ piglet	0.58	0.52	0.65
Water use, liter/piglet	462	328	614
Energy use, MJoule/piglet	827	718	971

3.2 Efficiency Analysis

Results of the various efficiency measures issuing from the input-minimising approach, are given in table 2. TE is 0.90, so improvement margins on the farm set is about 10%. Cost allocative efficiency is 0.97, improvement margin is about 3%. Total cost-minimising potential is about 13%. Improvement potential on environmental performance is larger for nitrogen, smaller for water and energy use.

Table 2: Statistics on the efficiency indicators.

Efficiency indicator	Average	Minimum	MaxiMum
Technical efficiency	0.903	0.786	1
Cost allocative efficiency	0.969	0.846	1
Nitrogen all. efficiency	0.918	0.737	1
Water use all. efficiency	0.986	0.932	1
Energy use all. efficiency	0.977	0.879	1

3.3 Trade-offs Analysis

Figure 1 show the link between CAE and NAE. A majority of farms face a win-win when substituting inputs for optimising costs: they will also win on environmental performance. A minority faces trade-offs. This confirms theoretical derivations (Lauwers, 2009). More atypical is, e.g. the link between NAE and WAE (Figure 2). Other pairwise comparisons yielded much more blurred information.

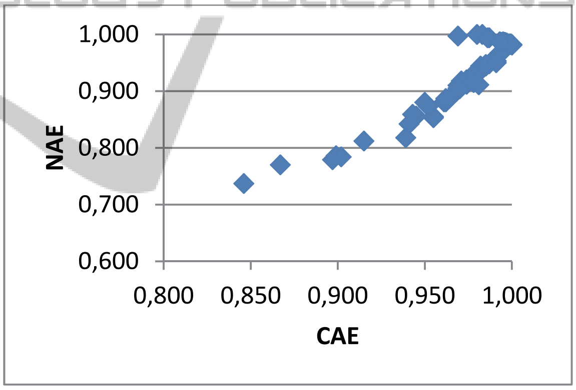

Figure 1: Win-win and trade-offs between cost (CAE) and nitrogen allocative efficiency (NAE).

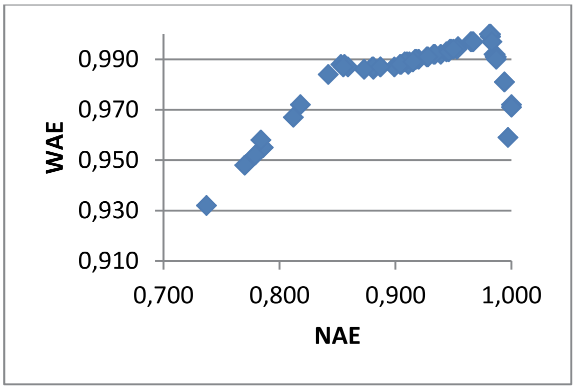

Figure 2: Win-win and trade-offs between nitrogen (NAE) and water use allocative efficiency (WAE).

4 DISCUSSION

The research reported in this paper confirms, to some extent, previous trade-offs analysis results, found for only one economic and one environmental performance indicator (Van Meensel et al., 2010). However, challenging observations are made and needs further discussion. Some of the pair-wise trade-off analyses deviate strongly from the ideal-type differentiation between win-wins and trade-offs. Moreover, extra inputs, e.g. labour and capital, further blur this picture. Finally, improvement margins seem rather low, which is not a big problem, because small differences at the cost minimisation side will be leveraged to bigger relative differences at profit level, but the problem rather becomes one of detecting causal links.

As the conventional approach show some inconveniencies, other types of models need to be explored on their ability to provide equivalent information. From literature, we see at least three eligible types of directional distance functions: one based on a directional vector that is firm-specific (see also Picazo-Tadeo et al., 2012), another based on a profit maximisation model (see e.g. Singbo and Lansink, 2010), and finally a similar one for materials balance minimisation.

5 CONCLUSIONS

Environmentally adjusted data envelopment models, built in an analogous way to the economic efficiency model, yield allocative efficiency scores that support economic-ecological trade-offs analysis. This confirms that earlier work can be generalised, but the multiple outcome (economic plus three environmental) comparison that has been done in this paper reveals that other paths for a more integrated eco-efficiency and trade-offs analysis are necessary. Eligible is the use of directional distance functions.

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