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Interfaces with Other Disciplines

Accounting for externalities and disposability: A directional economic environmental distance function

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ABSTRACT

The existence of positive and negative externalities ought to be considered in a productivity analysis in order to obtain unbiased measures of efficiency. In this research we present an additive style, data envelopment analysis model that considers the production of both negative and positive externalities and permits a limited increase in input utilisation where relevant. The directional economic environmental distance (DEED) function is a unified approach based on a linear program that evaluates the relative inefficiency of the units under examination with respect to a unique reference technology. We discuss the impact of disposability assumptions in depth and demonstrate how different versions of the DEED model improve on models presented in the literature to date.

1. Introduction

Modelling production which takes into account any externalities in the process within a productivity framework has become a topic of growing interest over the last decade. The concepts of efficiency and performance in conjunction with issues of environmental sustainability are of almost equal importance in our gradually wealthier societies. As stated in Seiford and Zhu (2002), both desirable and undesirable output may be present in the production process. In the extant literature, different industries have been analysed taking into account negative externalities such as biological oxygen discharges and total suspended solids in the pulp and paper industry (Hailu & Veeman, 2001), the residue ratio (i.e., the ratio between material inputs and waste) in solid waste collection and sorting programs (Courcelle, Kestemont, Tyteca, & Installé, 1998), air pollutants (e.g., dust, NO_x and SO_2) in electricity production (Korhonen & Luptacik, 2004; Yang & Politt, 2010; Zhou, Ang, & Poh, 2008), environmental pressure indicators in industrial systems (Zhang, Bi, Fan, Yuan, & Ge, 2008), and noise and delays in the transport sector (Lozano & Gutierrez, 2011; Yu, 2004; Adler et al. 2012). This argument is equally relevant for input variables in particular with respect to transport and communications networks although accounting for positive externalities has been less developed in the published literature to date.

The common procedure adopted in the literature in order to measure environmental performance is to incorporate undesirable outputs in the traditional data envelopment analysis (DEA) framework through data transformations. Koopmans (1951), Chung et al. (1997), Dyckhoff and Allen (2001), Sarkis and Talluri (2004), Seiford and Zhu (2002) and Gomes and Lins (2008) present different approaches to including negative externalities within a productivity framework. Scheel (2001) and Zhou et al. (2008) survey and discuss various DEA models that account for undesirable outputs. Most of the existing studies are based on the concept of radial efficiency measures despite Färe and Lovell (1978) who pointed out the shortcomings of radial measurements in this context. Radial measures of efficiency tend to overestimate technical efficiency particularly in the case of nonzero slacks present in the optimal solution. In order to consider slacks, the authors suggested the concept of non-radial measures such as an input-oriented Russell measure that minimises such input slacks. Similar issues were addressed by Charnes et al. (1985) which present an additive model that maximises the sum of both input and output slacks. The principal drawback of the latter approach is that input and output slacks are summed without accounting for the different measurement units. To overcome the problem, Lovell and Pastor (1995) develop the weighted additive model which ensures units and translation invariance by normalising the data. Tone (2001) proposes a slack based model that maximises normalised input and output slacks while Cooper, Park, and Pastor (1999) and Cooper, Pastor, Borras, Aparicio, and Pastor (2011) present respectively a range adjusted measure and a bounded adjusted measure that maximise input and output slacks in a non-oriented model. Fukuyama and Weber (2009) combine the directional distance function technology and the slack based measure in order to develop a generalised measure of technical efficiency. In this research we develop an additive type model

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that benchmarks the decision making units (DMUs) on a unique eco-environmental frontier taking into account the production of both positive and negative externalities. The directional economic environmental distance (DEED) function estimates the distance of each DMU to the efficient frontier given quantities and prices (costs), hence evaluates the potential monetary savings available were all DMUs to lie on the frontier. Prices and/or marginal damage costs are frequently available today because negative externalities are often given values through scientific research or international organisations such as the International Panel on Climate Change. Moreover, the growing interest in environmental issues has created markets for pollutants such as the EU Emissions Trading Scheme. However, we acknowledge that price information is not always available particularly when a market does not exist, therefore we also propose two alternative DEED approaches that do not require the use of prices, namely a range adjusted measure and a slack based measure.

As suggested by Dyckhoff and Allen (2001), the standard assumption that considers all inputs as resources to be reduced is no longer valid in an ecological context. From an eco-environmental perspective, ecological inputs (e.g., waste utilised in a power or recycling plant) ought to be maximised (Liu, Meng, Li, & Zhang, 2010; Sharp, Meng, & Liu, 2007). Moreover, following the same perspective, certain inputs may be increased to a limited extent in order to reduce the production of negative externalities and achieve greater eco-environmental efficiency. The idea of input increases was first presented in Cooper, Park, and Ciurana (2000), in which the computation of marginal rates and elasticities of substitution led to a modified additive model in which some of the input and the output slacks were allowed to be defined as positive or negative. Sueyoshi and Goto (2011) present a range adjusted measure incorporating the possibility of increasing input utilisation through a non-linear DEA model in which positive and negative slacks are present for the same input. However, the presence of a double slack per input creates problems in the definition of the efficient frontier and in particular in the selection of the benchmarks for the inefficient units. In the DEED model we therefore develop a unified approach that considers inputs which may be either decreased or increased (defined in this paper as flexible inputs) and inputs that may only be decreased (defined in this paper as standard inputs). Flexible inputs that may be increased will generally be limited depending on the context, for example by the potential increase of output production, thus accounting for budget or other resource restrictions. Our approach is based on a linear program which guarantees a feasible solution should one exist and solves the current problem of benchmark selection.

The aims of this paper are four-fold: (i) to clarify the impact of modelling choices on the technology set with respect to externalities because these concepts have not been clearly documented to date, (ii) to develop a DEA additive measure based model which, meeting the principal technology assumptions, includes the concept of flexible inputs within an eco-environmental efficiency analysis, (iii) to provide different methodological approaches as a function of the level of information available (i.e. price/cost information) and (iv) to compare the DEED framework with existing models in the literature thus highlighting the main advantages and disadvantages of each approach.

The remainder of the paper is organised as follows: in Section 2 we discuss the underlying assumptions and develop mathematical formulations for a variety of DEED models. In Section 3, we analyse the results of the model through a simple illustration and then compare the results to those of Sueyoshi and Goto (2011) and Sharp et al. (2007). The comparisons cover electric power production and a waste water plant, highlighting the versatility of the framework proposed. Finally, Section 4 concludes our research by summarising the potential advantages from applying a DEED approach and suggesting potential future directions.

2. Methodology

In Section 2.1 we discuss current approaches to modelling externalities and their respective assumptions in the DEA framework. Our aim is to clarify the impact of the different assumptions on the technology set because there is a lack of consensus surrounding these concepts. In Section 2.2 we present the generalised economic-environmental directional distance function by first describing the axioms (i.e. the mathematical constructs of the production possibility set and disposability assumptions) and then the complete model. In Section 2.3 we highlight the differences in the efficiency measure between the DEED model and the directional distance function approach. Finally, in Section 2.4 we adapt the potential paths to the frontier by applying slack-based, range-adjusted and bound-adjusted measures, none of which require price or marginal damage cost information.

2.1. Negative externalities and reference technology

Multiple models have been published in the literature to date with the intention of including negative externalities within a data envelopment analysis framework. Negative externalities may be introduced either (i) as input, (ii) as output to be reduced or (iii) through data transformation (Scheel, 2001). Consider an input vector $x \in R^n_+$ used to produce an output vector $y \in R^m_+$. The production technology is characterised by the technology set $T = \{(x, y) \mid x \text{ can produce } y\}$. When negative externalities are modelled as inputs, it is assumed that the input vector $x = (x^S, u)$ is composed of a sub vector x^S denoting the original inputs and a subvector u which denotes the negative externalities. If this is the case, the technology set is characterised by $TI = \{(x^S, u, y) \mid (x^S, u) \text{ can produce } y\}$. As shown in Fig. 1a, holding y constant and modelling negative externalities as input implies substitution between u and x^S. Moving along the frontier from point A to point C (i.e., on the input isoquant) implies a decrease in the original input in favour of an increase in negative externalities and vice versa while producing the same amount of output. This substitution effect is context dependent, for example investing in technology may lead to a reduction in pollution and increasing the number of hospital staff may lead to a reduction in hospital readmissions. However, it is not relevant when the two sets of variables are not substitutes, for example a reduction in fuel consumption is likely to lead to an equivalent reduction in CO_2 emissions.

Fig. 1b presents the production possibility set defined by the negative externalities vector (u) and the output vector y holding x^Sconstant, as expressed in TI for a constant returns to scale (CRS) and a variable returns to scale (VRS) technology set. In the case of CRS technology, TI is a linear function crossing segment (0A) and upwards. In the case of a VRS technology, TI would be bounded by the segments (aA, AB) and the horizontal extension from B. This technology simply resamples an input–output set and, as noted in Färe and Grosskopf (2003), implies that u may be freely disposable producing a physically impossible unbounded extension to the right of observation B. Nonetheless, this unbounded extension is purely an artefact of the definition of the technology set and, as highlighted in Hailu (2003), the measures of productivity would not direct inefficient observations to this section of the frontier.

When modelling negative externalities as output, disposability is an axiom of particular interest. Assume that we use an input vector x in order to produce a vector $y = (y^G, u)$ where the subvector y^G denotes the desirable outputs while the subvector u represents the negative externalities such that $TO = \{(x, y^G, u) \mid x \text{ can produce } (y^G, u)\}$. Färe, Grosskopf, and Pasurka (1989) develop the weak disposability assumption by treating desirable output as freely disposable (i) and negative externalities as weakly disposable (ii) as follows: