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Research article

Environmental efficiency of energy, materials, and emissions

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ABSTRACT

This study estimates the environmental efficiency of international listed firms in 10 worldwide sectors from 2007 to 2013 by applying an order-m method, a non-parametric approach based on free disposal hull with subsampling bootstrapping. Using a conventional output of gross profit and two conventional inputs of labor and capital, this study examines the order-m environmental efficiency accounting for the presence of each of 10 undesirable inputs/outputs and measures the shadow prices of each undesirable input and output. The results show that there is greater potential for the reduction of undesirable inputs rather than bad outputs. On average, total energy, electricity, or water usage has the potential to be reduced by 50%. The median shadow prices of undesirable inputs, however, are much higher than the surveyed representative market prices. Approximately 10% of the firms in the sample appear to be potential sellers or production reducers in terms of undesirable inputs/outputs, which implies that the price of each item at the current level has little impact on most of the firms. Moreover, this study shows that the environmental, social, and governance activities of a firm do not considerably affect environmental efficiency.

1. Introduction

When addressing the environmental problems facing firms or implementing new environmental policies, it is important to understand how firms operate their business in terms of the environment and efficiency. In the environmental performance analysis literature, both parametric and non-parametric approaches are used to estimate environmental efficiency in empirical studies. In particular, two of the main non-parametric methods are data envelopment analysis (DEA) and free disposal hull (FDH), which have been used in many publications (Cazals et al., 2002; Cherchye et al., 2001; De Witte and Marques, 2010; Färe et al., 1996, 2005; Lee et al., 2002; Ishinabe et al., 2013).

Both DEA and FDH are characterized by a lack of assumptions about the particular functional form of the production frontier and can estimate a best-practice frontier from observed data. However, a problem with DEA/FDH is that the best-practice frontier could be sensitive to super-efficient outliers (Cazals et al., 2002; Daraio and Simar, 2007; Tauchmann, 2011). In other words, when sample size is sufficiently large, a best-practice frontier estimated by DEA/FDH could be overestimated due to super-efficient peer decision making units (DMUs). Therefore, DEA/FDH efficiency scores that lack a deep examination of super-efficient DMUs, as in many publications, show just the upper limit of the score on the potential production frontier (for a review of treatment of outliers within the Journal of Environmental Management, see Supplementary material S1). The same is true for environmental efficiency analysis that uses DEA/FDH without considering super-efficient DMUs because the estimated score tends to be too efficient to be operational for most DMUs.

This suggests that a sensibility analysis should be conducted on DEA/FDH. To avoid the problem of outliers, Cazals et al. (2002), Daraio and Simar (2007), and Tauchmann (2011) propose the order-m method, which is based on FDH using subsampling bootstrapping to create peer DMUs and enables sensitive analysis of

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FDH.

The aim of this study is to develop a sensitivity analysis method for efficiency estimates, and to apply the proposed method to evaluate current situation of environmental efficiency among listed firms worldwide in 2007–2013. This study first examines the order-m method to technically evaluate environmental efficiency among DMUs, and develops a method of shadow price estimation to economically evaluate DMUs. We consider the development of order-m in the directional distance function in this paper is the most important contribution into the existing literature. From the viewpoint of empirical study, this study then evaluates the environmental efficiency of listed firms worldwide technically (order-m) and economically (shadow price estimation). In addition, this study provides insights into the characteristics of technically efficient firms, as a second step analysis, using a regression model.

The primary motive of this study is to examine the environmental efficiency of international listed firms by adopting the order-m method of the directional distance function. This study considers each of ten undesirable inputs/outputs in ten respective models. Using an output (i.e., gross profit, which is sales minus the cost of goods sold) and two inputs (labor and capital), we consider each of the following items to be undesirable inputs/outputs. Total energy consumption, electricity use, water use, and paper consumption are considered to be undesirable inputs (energy and material uses); Scope 1, Scope 1 + 2, Scope 1 + 2 + 3, sulfur oxides (SOx), nitrogen oxides (NOx), and volatile organic compounds (VOC) are undesirable outputs (emissions). Note that, Scope 1, 2, and 3, which are greenhouse gas (GHG) emission categories, are defined in GHG Protocol (see World Resources Institute and World Business Council for Sustainable Development, 2011, p.140) as follows: "(Scope 1) emissions from operations that are owned or controlled by the reporting company; (Scope 2) emissions from the generation of purchased or acquired electricity, steam, heating or cooling consumed by the reporting company; (Scope 3) all indirect emissions (not included in Scope 2) that occur in the value chain of the reporting company, including both upstream and downstream emissions."

In examining the environmental efficiency of the order-m method, this study analyzes two additional topics. One is the calculation of the shadow prices, which indicate the maximum acceptable prices for certain firms/plants if markets exist, for each of the ten input/output items. Another topic is the examination of which activities affect the firms' environmental efficiency using a regression model as a second step. Regarding the former topic, the shadow prices indicate the opportunity costs for the firms/plants to reduce each item by one unit. To address environmental problems, policy makers are often required to create markets or impose heavier taxes on environmental resources/emission credits. If a market is created for undesirable inputs and outputs to be traded or an environmental tax rate is increased, the shadow price will hint at how many firms/plants will be potential buyers or sellers of the item and indicate the potential effect of creating such markets as emission trading scheme or policy implementation. In other words, comparing the shadow prices to the actual market price could indicate a gap between a buyer (i.e., a production expander) and seller (i.e., production reducer).

This study applies two methods for calculating shadow prices, which are called order-m specification and parametric liner programming (LP) specification in this study. Regarding order-m specification, this study derives the relative shadow prices from the estimated solutions to the dual problem of order-m estimation. Although this method is often used in DEA, it faces the challenge that dual variables (i.e., shadow prices in the dual DEA/FDH problem) often take a value of zero, which results in positive infinity shadow prices (for a similar case of FDH relative prices, see Kuosmanen et al. (2006)). To overcome this challenge, this study simply uses values without rounding close-to-zero values to zero to avoid the problem by force. In a more sophisticated way, the Appendix shows a procedure for estimating the upper and lower bounds of the shadow price. In addition, in a more indirect manner, this study uses parametric LP specification (Chambers, 2002; Fukuyama and Weber, 2008), which restores the convexity with a quadratic production function. The parametric LP specification smooths the values on the order-m production frontier over a quadratic production function and estimates the partial derivatives of the order-m score.

To examine what characteristics of firms affect calculated environmental performance, this study aims to find empirical evidence on the relationship between the environmental, social, and governance (ESG) activities of firms and efficiency levels. If ESG activities improve efficiency, investment in the activities can be interpreted as generating a return. On the other hand, if the ESG activities reduce efficiency, investment in these activities is interpreted as causing a loss.

The structure of this study is as follows: Section 2 presents our model and the method for estimating shadow prices; Section 3 explains the dataset used in this study; Section 4 presents the estimated results and concludes.

2. Model

2.1. Preliminary construction

Suppose that there are N DMUs, and a certain DMU, i, belongs to a set of DMUs, S: $i \in S$. Let $x \in R_+^J$, $y \in R_+^K$, and $b \in R_+^L$ denote the vectors of inputs, desirable outputs and focal undesirable (i.e., environmentally bad) inputs/outputs, respectively, in the Euclidean space, R_+^{J+K+L}. b consists of bad inputs, b^{in}, and/or bad outputs, b^{out}, and could also be expressed as $b \in \{b^{in}, b^{out}\}$. The true technology production set, T, in this study is defined in the Euclidean space, R_+^{J+K+L}, as follows:

$$T = \left\{ (x, y, b) \in R_+^{J+K+L} \middle| \left(x, b^{in}\right) \text{ can produce } \left(y, b^{out}\right) \right\} \tag{1}$$

where $b \in \{b^{in}, b^{out}\}$.

Following Deprins et al. (1984/2006) and Cherchye et al. (2001), this study adopts FDH approximation to estimate the true technology set, T, by the observed DMUs. FDH is originally based on two minimal assumptions: the technology set, T, should envelop all observed data, and all inputs (x, b_{in}) and outputs (y) are freely (or strongly) disposable.

In adopting environmentally undesirable outputs, b^{out}, earlier DEA studies often assume weak disposability of undesirable outputs (e.g., Färe et al., 1996). Under weak disposability, the desirable and undesirable outputs (y, b^{out}) are both assumed to be weakly disposable as follows: if $(x, y, b^{in}, b_0^{out}) \in T$, then $(x, \alpha y, b^{in}, \alpha b_0^{out}) \in T$ where $0 < \alpha < 1$. On the other hand, weak disposability is seldom assumed in FDH approximation because FDH analysis is based on free (strong) disposability. Following Ray and Mukherjee (2007) and De Witte and Marques (2010), this study instead assumes reverse disposability of undesirable outputs, which is similar to the assumption of free disposability. A certain level of desirable outputs, which is associated with a lower level of undesirable outputs, could be generated with a higher level of undesirable outputs. This assumption could be specifically represented as follows: if $(x, y, b^{in}, b_0^{out}) \in T$ and $b_1^{out} \geq b_0^{out}$, then $(x, y, b^{in}, b_1^{out}) \in T$.

Based on the two minimal assumptions and reverse disposability described above, we consider empirical approximation of FDH in the directional distance function form of primal/dual