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On estimating shadow prices of undesirable outputs with efficiency models: A literature review

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HIGHLIGHTS

- Over 40 studies on shadow price estimation for undesirable outputs are reviewed.
- The general shadow pricing framework is described.
- We summarize the main methodological and application aspects of existing studies.
- The shadow price estimation of CO_2 emissions received increasing attention.
- The regions concerned were shifting from western to Asian countries.

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ABSTRACT

Undesirable outputs (or bads) refer to the byproducts accompanied with desirable outputs (or goods) in a production process, e.g. sulfur dioxide and carbon dioxide in coal-fired power generation. The shadow price of undesirable output, which may be interpreted as the opportunity cost of abating one additional unit of undesirable output in terms of the loss of desirable output, could provide valuable reference information for policy analysis and making. A prevalent practice is to use the Shephard or directional distance function to derive the shadow price, which can be further calculated by parametric or nonparametric efficiency models. In application, earlier studies have estimated shadow prices at plant, sector and even economy levels. This study aims to conduct a systematic review of the studies on estimating shadow prices of undesirable outputs with efficiency models. We first introduce the methodological framework for deriving shadow prices as well as the nonparametric/parametric efficiency models for calculating their values. A systematic summary of over forty earlier studies in this field is then conducted, through which the key features of the existing studies are summarized and possible future research directions are identified.

1. Introduction

Undesirable outputs (or bads) refer to the byproducts accompanied with desirable outputs (or goods) in a production process. For instance, electricity generation in a fossil-fuel fired power plant will inevitably produce undesirable outputs such as SO_2 and CO_2 emissions. The production of undesirable outputs often has negative impacts on the natural environment and the sustainable development of society and economy. At global level, most countries have enacted diverse environmental policies for controlling undesirable outputs, e.g. pollution penalty, carbon tax and emissions trading scheme. Theoretically, Pittman [1,2] has pointed out the necessity of incorporating undesirable outputs into efficiency and productivity analysis when productive entities are subject to environmental regulations.

The reduction of undesirable outputs can be achieved through different ways such as capital investment and shrinkage of production activity, which may require additional inputs or result in the loss of desirable outputs. Marginal abatement cost refer to the costs associated with eliminating an additional unit of undesirable output, which tends to rise with the decrease in the amount of undesirable output. The use of marginal abatement costs is often

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linked to marginal abatement cost curves, which can be derived through different methods. The concept of shadow price provides one important way for estimating or approximating the marginal abatement cost of undesirable outputs. The shadow price of an undesirable output can be generally interpreted as the opportunity cost of reducing one additional unit of undesirable output in terms of less production of desirable outputs [3] or more use of "good" inputs [4]. Their relationships are more clearly described by the shadow pricing formulas given in Section 3.1. It is widely believed that the shadow price of undesirable output provides valuable reference information for the implementation of environmental and carbon policies such as environmental/carbon taxation.

The shadow prices of undesirable outputs are usually derived from the market prices of desirable ouptuts by using distance functions and duality theory, which can be further calculated by parametric or nonparametric efficiency models. Many earlier studies have been devoted to explore the theoretical and application aspects of distance functions in estimating the shadow price of undesirable outputs. For instance, both the Shephard distance function and the directional distance function have been successively employed in the shadow pricing procedure. In application, previous studies on estimating shadow prices mainly concentrated upon single polluting industries, such as electricity, paper and pulp and agriculture, while the shadow pricing for multi-sector and multi-region has also been studied. With the growing concern on global warming, the shadow price of CO_2 emissions has received increasing attention in recent years. Although the literature survey by Zhou et al. [5] mentioned several studies on applying data envelopment analysis (DEA) models to shadow price estimation, there is still a lack of a comprehensive review on the use of efficiency models to estimate the shadow prices of undesirable outputs. With the increase of the number of relevant studies, a literature review is necessary and timely since it can provide researchers the insights on the past developments and future directions of this field. It is therefore the purpose of this study to conduct a systematic review of studies on using efficiency models to estimate the shadow prices of undesirable outputs.

In the sections that follow, we first introduce the concept of environmental production technology and the popular distance functions with different mapping rules. Next, we provide a sketch of the general procedure to estimate the shadow price of undesirable outputs with parametric/nonparametric efficiency models. The main application features of previous studies and several methodological extensions are then summarized and discussed, through which five future research directions are identified.

2. Distance functions

2.1. Environmental production technology

Consider a joint-production process in which a productive entity employs the input vector $x \in \Re^I_+$ to produce the desirable output vector $y \in \Re^J_+$ and the undesirable output vector $b \in \Re^K_+$. The input vector often includes both energy and non-energy inputs, and the undesirable output vector includes a variety of pollutants or/and greenhouse gases. The production technology can be represented by the output possibility set $P(x) = \{(y,b) : x \text{ can produce}(y,b)\}$ or the input requirement set $I(y,b) = \{x : \text{ producing } (y,b) \text{ requires } x\}$.

In the joint-production process, inputs and the desirable output are generally assumed to be strongly or freely disposable [6], which can be respectively expressed as follows:

$$\begin{aligned} &x' \geqslant x \text{ implies } P(x') \supseteq P(x) \text{ or} \\ &x \in I(y,b) \text{ implies } x/\theta \in I(y,b)\ \forall\ 0 \leqslant \theta \leqslant 1 \end{aligned} \quad (1)$$

$$\begin{aligned} &(y,b) \in P(x) \text{ and } y' \leqslant y \text{ imply } (y',b) \in P(x) \text{ or} \\ &x \in I(y,b) \text{ and } y' \leqslant y \text{ imply } x \in I(y',b) \end{aligned} \quad (2)$$

Under the circumstance of environmental regulations, the undesirable outputs cannot be freely disposable, i.e. the productive entity has to undertake a certain amount of cost to reduce the undesirable outputs. Furthermore, the undesirable outputs will be inevitably produced unless the entire production process is terminated. The two important assumptions, which are respectively referred to as weak disposability and null-jointness, make the production technology to be an environmental production technology (or polluting technology). Mathematically, the two assumptions can be respectively given by

$$\begin{aligned} &(y,b) \in P(x) \text{ and } 0 \leqslant \theta \leqslant 1 \text{ imply } (\theta y, \theta b) \in P(x) \text{ or} \\ &x \in I(y,b) \text{ and } 0 \leqslant \theta \leqslant 1 \text{ imlpy } x \in I(\theta y, \theta b) \end{aligned} \quad (3)$$

$$\begin{aligned} &\text{if } (y,b) \in P(x) \text{ and } b = 0, \text{ then } y = 0 \text{ or} \\ &\text{if } x \in I(y,b) \text{ and } b = 0, \text{ then } y = 0 \end{aligned} \quad (4)$$

2.2. Definition of alternative distance functions

Distance functions are often employed to characterize the environmental production technology described above. The Shephard distance function provides a theoretical foundation on measuring efficiency and productivity of productive entities. Färe et al. [7] incorporated undesirable outputs into the Shephard distance functions and proposed a novel framework for estimating the shadow prices of undesirable outputs. In Färe et al.'s framework, a translog Shephard output distance function was used to characterize the production technology and the parameters were estimated by solving a deterministic optimization model. This line of thought has led to a number of studies as summarized in Section 4.

Following Shephard [8], Färe et al. [7] and Coggins and Swinton [9], we define the following Shephard output distance function with undesirable outputs:

$$D_o(x,y,b) = \inf\{\theta > 0 : (y/\theta, b/\theta) \in P(x)\} \quad (5)$$

where θ is the value of the output distance function that measures the maximum degree by which (y,b) can be proportionally increased given x. Likewise, according to Shephard [8], Färe and Grosskopf [10], Färe and Primont [6] and Hailu and Veeman [3], the Shephard input distance function can be defined as follows

$$D_t(y,b,x) = \sup\{\phi > 0 : (x/\phi) \in I(y,b)\} \quad (6)$$

where ϕ is the value of the input distance function that measures the maximum degree by which x can be proportionally reduced given (y,b). Table 1 shows several important properties of the Shephard output and input distance functions with reference to environmental production technology.

The Shephard distance function attempts to adjust the desirable and undesirable outputs at the same rate, which may not be consistent with the common desire of public and policy makers to reduce undesirable outputs and increase desirable outputs simultaneously. An important development is the directional distance function that was proposed to "*allow for the possibility of crediting firms for the reduction of bad outputs*" [11,12]. Recently, the directional distance function has received increasing attention in energy and environmental performance measurement mainly owing to its flexibility [5].[1] The Shephard distance function may

[1] It should be pointed out that certain variations of the Shephard distance function, e.g. hyperbolic efficiency measure, can also be used to model the simultaneous expansion of desirable outputs and contraction of undesirable outputs. .However, the directional distance function succeeds in integrating all the variations and provides a more general framework for modeling production technology.

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