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A critical review of the main methods to treat undesirable outputs in DEA

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Abstract
The treatment of undesirable outputs in Data Envelopment Analysis (DEA) has received great research attention recently. As such and as are presented in this work, there are four possible options to deal with those: first ignoring them from the production function; second treating them as regular inputs; third treating them as normal outputs and fourth performing necessary transformations to take them into account. Also new model propositions for their treatment are being presented. Each method brings with it, benefits and drawbacks which each researcher should take into account at every stage of their research and assess which method is more appropriate to be used.

Keywords: Environmental efficiency; DEA; undesirable outputs

JEL Codes: O44, Q56, N5

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1. Introduction

Data Envelopment Analysis (DEA) is a non-parametric approach applied to assess the efficiency of Decision Making Units (DMUs) into consideration with the use of linear programming techniques (Boussofiane et al., 1991). Efficiency is the ratio of output per input and usually the inputs include production elements, such as labour, capital, land, materials, fuel, machinery, and equipment whereas the outputs consist of production volume, production value, sales, value-added, and GDP (Tamaki et al., 2016). DEA models are either input-oriented minimising inputs or output-oriented models maximizing outputs without requiring more inputs and there should also be no obvious linear relationship among inputs and outputs in DEA models (Wu et al., 2013).

A common issue that has occurred in DEA is how to account for undesirable outputs in the production process. The current understanding is that researchers should praise DMUs for their provision of desirable or marketable outputs and penalise them for their provision of undesirable outputs (Yang and Pollitt, 2010). If inefficiency exists in the production, the undesirable pollu[1]tants should be reduced to improve the inefficiency and should be treated differently (Seiford and Zhu, 2001).

Many approaches have been put forward to account for this which are divided into direct and indirect ones; direct approaches refer to approaches that treat the undesirable output in its original form such as parametric output and input distance functions (Fare et al., 1993; Coggins and Swinton, 1996; Hailu and Veeman, 2001; Ho et al., 2017) and DEA methods (Skevas et al., 2012; Serra et al., 2014; Kabata, 2011; Yang et al., 2008; Skevas et al., 2014; Ramli et al., 2013).

[1] For more information on air pollutants and their modelling see among others Halkos (1992, 2007, 2012), Halkos and Kitsos (2015), Halkos and Tsilika (2015), Halkos et al. (2016) and for implementing environmental management systems standards Evangelinos and Halkos (2002).

On the other hand indirect approaches refer to treating the undesirable output as a classical input, whereas the undesirable output is moved to the input side of the model after some transformation and treated as one of the inputs (Mohd et al., 2015), as both inputs and undesirable outputs are the values that need to be minimised and therefore it is acceptable to treat both in the same manner. However, Seiford and Zhu (2001) highlighted that treating undesirable outputs as inputs will distort the actual production process since the relationship between inputs and outputs in the actual production process will be lost.

Many authors have focused on treating undesirable outputs, some of the most commonly cited works include: Fare et al (1989, 2000), Yaisawarng and Klein (1994), Lovell et al (1995), Fare and Grosskopf (1995, 2003, 2004), Thanassoulis (1995), Tyteca (1996), Rheinhard et al (1999, 2000), Scheel (2001), Hailu and Veeman (2001), Zofio and Prieto (2001), Dyckhoff and Allen (2001), Sun (2002), Seiford and Zhu (2002); Murtough et al (2002), Kumar and Khanna (2002), Korhonen and Luptacik (2003), and Gomes (2003).

The structure of the paper is as follows. Section 2 reviews the main methods for treating undesirable outputs with section 3 discussing those and their implications. Finally, the last section (section 4) concludes the paper.

2. Summary of methods for treating undesirable outputs

Dealing with undesirable outputs will ultimately affect DMUs' efficiencies. A production function shows strong disposability of undesirable outputs if these are freely disposable; whereas weak disposability links pollutants' reductions with lower production of desirable outputs, such as for instance CO_2 emissions which cannot be reduced using the existing available technologies (Halkos and Polemis, 2018). The most common methods for treating undesirable outputs in DEA and the relevant production function are presented below.

2.1 Ignoring undesirable outputs

The first option to treat undesirable outputs is to simply disregard them from the production function. Ignoring the undesirable implies that they have no value in the final evaluation and may thus provide misleading results (Yang and Pollitt, 2009). Environmental undesirable outputs cannot be separated from the associated desirable output and a reduction in an undesirable output brings also a reduction in the relevant desirable outputs (Halkos and Polemis, 2018).

2.2 Treating undesirable outputs as inputs

Another option is to treat undesirable outputs as normal inputs in the production function. For example Korhonen and Luptacik (2004) measured the eco-efficiency of 24 coal-fired power plants in a European country and their modelling methods resembled those used in Tyteca (1996, 1997) who treated emissions directly as inputs in the sense that both inputs and undesirable outputs should be decreased.

In addition Reinhard et al. (2000) calculated the environmental efficiency for Dutch dairy farms in the presence of multiple environmentally damaging inputs and compared two methods of Stochastic Frontier Analysis (SFA) and DEA. Furthermore this approach has been used for Canadian pulp and paper industry (Hailu and Veeman, 2001), Dutch sugar beet growers (De Koeijer et al. 2002) and greenhouse firms in the Netherlands (Lansink and Bezlepkin, 2003). The extent of Japanese banking inefficiency and the shadow price of problem loans were studied by Hirofumi and William (2008) in which case they modelled those loans as a jointly produced undesirable by-product of the loan production process. Yang and Michael (2010) stressed that these approaches inevitably assume undesirable outputs are strongly disposable.

Amirteimoori et al. (2006) extended the standard CCR (Charnes et al., 1978) model to a DEA like model dealing with the relative efficiency via increasing undesirable inputs and decreasing undesirable outputs. Also Jahanshahloo et al. (2005) presented an approach to treat both undesirable inputs and outputs at the same time in non-radial DEA models. More recently Farzipoor Saen (2010) proposed a model for supplier selection in the presence of both undesirable outputs and imprecise data.

2.3 Treating the undesirable outputs in the non-linear model

A further approach simply treats the undesirable outputs as outputs in the production function. Fare et al. (1989) applied the nonparametric approach on a 1976 data set of 30 US mills which use pulp and three other inputs in order to produce paper and four pollutants, whereas they assumed weak disposability for undesirable outputs. Their results showed that depending on the use or not of undesirable outputs, the performance rankings of the DMUs were quite sensitive. Therefore traditional DEA models might show a biased indication of the current situation. Other studies present similar results (Pittman, 1983; Tyteca, 1996, 1997). All these studies employ a direct approach in which both desirable and undesirable outputs are treated in their actual format. In those cases it is assumed that desirable outputs are strongly disposable, while the undesirable outputs are assumed to be weakly disposable because their values cannot be augmented without affecting the values of other desirable outputs (Fare et al., 1989).

Chung et al. (1997) and Ball et al. (2004) extended the idea of Fare et al. (1989) and proposed the use of directional distance functions (DDF) to evaluate efficiency of DMUs when the production function also produces some undesirable outputs. In this approach the desirable outputs can be expanded and the desirable inputs and undesirable outputs can be reduced based on a given direction vector (Chung et al., 1997).

The directional output distance function which aims to increase the desirable outputs and decrease the undesirable ones and the inputs directionally, is defined as shown below:

$$\vec{D}(x, y, b; g) = \sup\{\rho : (x - \rho g_x, y + \rho g_y, b - \rho g_b) \in T\}$$

where inputs are represented as $x \in R_+^N$, good outputs as $y \in R_+^M$ and bad outputs as $b \in R_+^J$.

Many researchers have pointed that a directional distance function (DDF) approach (suggested by Fare and Grosskopf, 2004) is the best solution as it allows for simultaneous increase in desirable outputs and reduction of undesirable outputs (Mohd et al., 2015).

Some examples of this use of undesirable outputs are presented in table 1.

Moreover following those lines Haynes et al. (1993) measured the relative efficiency in pollution prevention activities. By assuming free disposability of all inputs and outputs they used chemicals and chemical residues as inputs and outputs along with traditional inputs and outputs and measured technical efficiency (Halkos and Tzeremes, 2009; 2013a,b,c; 2014). Yaisawarng and Klein (1994) followed Fare et al. (1989) modelling strategy and examined the effect of SO_2 control on productivity change in US coal-fired power plants by imposing weak disposability on SO_2 emissions.

Lozano et al. (2013) put forward a DDF approach to deal with network DEA problems in which the processes may generate not only desirable outputs but also undesirable outputs. Kordrostami and Amirteimoori (2005) consider a multistage system and take into account the undesirable factors with a minus sign in the computation of the virtual inputs and virtual outputs of a multiplier formulation. Hua and Bian (2008) extend this approach to a more general network of processes.

There have been some objections to the weak disposability model such as those raised by Hailu and Veeman (2001) that “the weakly disposable approach leaves the impact of undesirable outputs on efficiency undetermined”, whereas Fare and Grosskopf (2003) responded that they disagree as the weakly disposable DEA model is consistent with physical laws and it allows the treatment of undesirable outputs showing the opportunity cost of reducing them.

Table 1: Examples of studies dealing with undesirable outputs

Study / authors	**Approach**
Arcelus and Arocena (2005)	DDF approach to evaluate the efficiency of 14 OECD countries.
Picazo-Tadeo et al. (2005)	Environmental efficiency of Spanish producers of ceramic pavements using weak disposability and DDF.
Fare and Grosskopf (2010)	Slacks based DDF approach.
Fukuyama and Weber (2009)	Slacks-based DDF approach to study Japanese bank.
Fukuyama et al. (2011)	Evaluate three Japanese railway companies.
Choi et al. (2012)	A non-radial slacks-based measure to study the energy related CO_2 emissions in China.
Mahlberg and Sahoo (2011)	Radial and non-radial Luenberger productivity indicators.
Barros et al. (2012)	Utilised Russell DDF to evaluate Japanese banks.
Zhou et al. (2012)	Non-radial DDF to evaluate the electricity generation in OECD and non-OECD countries.
Zhang et al. (2013)	Meta-frontier non-radial DDF in order to study electricity generation in Korea.
Cheng and Zervopoulos (2014)	Generalized DDF approach to measure the efficiency of health care systems in 171 countries.
Chen et al. (2014)	Providing a comprehensive efficiency measurement to estimate the performances of OECD and non-OECD countries.
Chen et al. (2015)	Proposes an enhanced directional distance measure model for dealing with desirable and undesirable outputs while allowing some inputs and outputs to be zero through the assessment of CO_2 emissions in 111 countries.
Tamaki et al. (2016)	Efficiency measurement of public transport in world cities.
Lee et al. (2017)	Productivity measurement in the airline industry and examination of the determinants of productivity change.

Zhou et al. (2012) proposed a non-radial slacks-based measure (SBM) model extended with the incorporation of undesirable outputs. This model is an extension of Tone's (2001) original SBM model and uses a ratio approach to strike a balance between undesirable output reduction and desirable output increase. It combines environmental and economic inefficiencies and provides a composite index for modeling economic environmental performance. Skevas et al. (2012; 2014) used DDF approach to propose a risk adjusted DEA model to determine the efficiency of Dutch arable farmers in the presence of undesirable outputs.

Moreover Sueyoshi and Goto (2012 a; b) introduce the concept of natural and managerial disposability in DEA analysis. Natural disposability shows that firms reduce their inputs in order to reduce their undesirable outputs, whereas managerial disposability shows that a firm increases its inputs in order to take advantage of the business opportunity after a change in environmental regulation. Finally Guo and Wu (2013) also treat the undesirable outputs as inputs, as from the perspective of profit, more undesirable outputs usually mean more inputs consumed and more costs.

2.4 Applying necessary transformations

Another approach is to apply a monotone decreasing transformation. Koopmans (1951) mentioned that some undesirable outputs like pollutant emissions and waste disposal affect negatively the environment and should be reduced. As such a first reaction is to apply some transformations as presented below:

a. (U)=−U; the so called the ADD approach suggested by Koopmans (1951), in which case the undesirable inputs or outputs will become desirable. Though then some data may become negative and it is not straightforward to define efficiency scores for negative data.

b. (U)=−U + β is another option (Ali and Seiford, 1990; Scheel, 2001; Seiford and Zhu, 2001), but this classification may depend on β.

c. The multiplicative inverse: f (U) = 1/U (Golany and Roll, 1989; Lovell et al., 1995).

Related to ADD, there are several recent works dealing with negative data (but desirable) with directional distance functions, such as Fare and Grosskopf (2004), Silva Portela et al. (2004) and Yu (2004). Those approaches are related to the weighted additive models so it is important to realise that the additive models are able to handle negative data (Seiford and Zhu, 2005).

In addition to the above mentioned approaches Cherchye et al. (2011) perform a transformation in the measurement scale based on a normalisation procedure, which can be applied both to desirable and undesirable outputs. This procedure provides indicators between 0 and 1. As data normalisation can lead to loss of information, this method is not commonly used in DEA studies (Zanella, 2004).

Halkos and Papageorgiou (2014, 2016) cover the gap in literature by providing a typical radial DEA model in three different settings in order to model regional environmental efficiency. More analytically based on Seiford and Zhu (2001, 2005) they use a linear transformation of bad output in order to model the pollutant as a regular output in a DEA formulation setting. Secondly it follows several other studies (Pittman 1981; Cropper and Oates 1992; Reinhard et al. 2000; Dyckhoff and Allen 2001; Hailu and Veeman 2001; Korhonen and Luptacik 2003; Mandal and Madheswaran 2010) treating the pollutant as a regular input. Finally the study uses the DEA formulation as proposed by Kuosmanen and Kortelainen (2005) and Kortlainen (2008) and the notion of eco-efficiency, therefore measuring regions' eco-efficiency levels in municipality waste generation.

2.5 New models

Recently some new models for treating undesirable outputs have come forward. Gomes and Lins (2008) propose a new approach to modelling undesirable outputs, based on the zero sum gains DEA models (ZSG-DEA). These models consider the production dependence among the DMUs (Gomes, 2003; Gomes et al, 2003, 2005; Lins et al, 2003) including as an additional restriction, the zero sum game property, in which whatever lost (or gained) by one of the players must be gained (or lost) by the others, that is the net sum of gains must be zero. This means that any DMU that wants to reach the efficient frontier by increasing the output (or decreasing the input) will make the others reduce (or increase) their values by this amount, in order not to change the total. In the case of pollutants, ZSGDEA models can be useful for the ecological economy (Sachs, 2000).

Huang et al. (2014) propose a model named US-SBM which combines super efficiency, undesirable outputs and slacks-based measure (SBM) together. Fukuyama and Weber (2010) propose a slacks-based inefficiency measure for a two-stage system with bad outputs and analyse the source of inefficiency, which also does not consider the super efficiency.

Mohd et al. (2015) proposed an enhanced risk adjusted efficiency model based on the DDF DEA approach developed by Skevas et al. (2014) that also includes climatic variability and used interval data approach to represent uncertainty data will be developed, called "Risk Adjusted Interval DEA Model with Undesirable Outputs and Climatic Variability Conditions".

Furthermore through using an environmental intensity index, the economy can expand without compromising the environment (Wursthorn et al. 2011). The general concept of Halkos et al. (2015) model is similar to Zaim's (2004) who applied directional distance functions and constructed two indices. The first index is an economic one in which inputs are used to produce economic outputs while the second environmental index uses economic output to produce undesirable environmental outputs. The ratio of these two indices is used in order to acquire the pollution intensity index. Chen et al. (2012) also constructed a sustainability index consisting of 'industrial design module' and 'bio design module' in their study of sustainable product design in the automobile industry.

3. Discussion

As described in the previous section, researchers have widely focused on how they can treat undesirable outputs in DEA in order to take them into consideration in the production function. The methods presented above show that researchers are divided in their approaches and under different scenarios different techniques might seem more appropriate than others. The first approach of simply ignoring undesirable outputs is disregarded by most authors as it does not make sense to simply ignore those and pretend they don't exist.

The second approach of treating undesirable outputs as inputs which has been widely used in research. Even so these perspectives have been criticised by academics (Hailu and Veeman, 2001; Fare and Grosskopf, 2003; Hailu, 2003). The central theme of this critique is the 'operationalization of weak disposability in empirical production analysis' (Kuosmanen, 2005). In those regards Kuosmanen (2005) pointed out that the common specification of weak disposability implicitly assumes that all DMUs in the sample apply a uniform abatement factor. Moreover Fare and Grosskopf (2003) mention some drawbacks but at the same time acknowledge that this approach is quite appealing and useful. The first is the free disposability assumption, since in reality unlimited increases in an undesirable output are not technically possible. Secondly when assessing power plants or energy sectors from a microeconomic perspective, the linkage between fuels, power and emissions should hold, as emphasised by Fare and Grosskopf (2005).

A further approach is treating those undesirable outputs as normal outputs in the production function. In those regards a direct approach is applied whereas both desirable and undesirable outputs are treated in their actual format. With the use of DDF it is possible to reduce the undesirable outputs based on a given direction vector (Chung et al., 1997). This type of DEA approaches has been widely used in environmental efficiency assessments (Arcelus and Arocena, 2015; Lozano and Gutierrez, 2008).

There have been some objections to the weak disposability model such as those raised by Hailu and Veeman (2001) that "the weakly disposable approach leaves the impact of undesirable outputs on efficiency undetermined", whereas Fare and Grosskopf (2003) responded that they disagree as the weakly disposable DEA model is consistent with physical laws and it allows the treatment of undesirable outputs showing the opportunity cost of reducing them.

Finally another option is to transform the undesirable outputs and several methods to do this have been presented in section 2.4. By using the outputs' reciprocals another transformation is possible as suggested by Lovell et al. (1995). This approach has also been used by Ramanathan (2006) who used the reciprocal of the CO_2 outputs in his study. A further transformation has been proposed by Seiford and Zhu (2001, 2005) which assumes strong disposability for all the variables including the transformed undesirable outputs. Data translation has also been used by Lu and Lo (2007) in their study of regional development in China and by Wang et al. (2014) for the needs of their two-stage DEA model. New models have also been put forward recently in treating undesirable outputs. These have not been widely tested yet, so it is not possible to ascertain their value.

As it has come forward from the previous analysis the decision to use each method depends on the user and each analysis he/she intends to perform. There is no straightforward answer in which method to use as each one has its advantages and disadvantages. Therefore every researchers should consider first what he/she wants to achieve from their analysis.

4. Conclusion

Treating undesirable outputs has been proven to be quite a challenge for researchers working on DEA. Four possible options have been presented in the previous sections along with some new model propositions that could be of use. To conclude the four most commonly used methods in treating undesirable outputs include:

1. ignoring them from the production function,
2. treating them as regular inputs,
3. treating them as normal outputs and
4. performing necessary transformations to take them into account.

As such each method has its benefits and drawbacks which each researcher should take into account at every stage of their research and assess which method is more appropriate to be used.

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