Desalination 249 (2009) 230–234

Contents lists available at ScienceDirect

Desalination

journal homepage: www.elsevier.com/locate/desal

Technical efficiency and cost analysis in wastewater treatment processes: A DEA approach

Francesc Hernández-Sancho [a,*], Ramón Sala-Garrido [b]

[a] Dept. of Applied Economics II, Faculty of Economics, Campus dels Tarongers, University of Valencia, 46022 Valencia, Spain
[b] Dept. of Mathematics for Economics, Faculty of Economics, Campus dels Tarongers, University of Valencia, 46022 Valencia, Spain

ARTICLE INFO

Article history:
Accepted 20 January 2009
Available online 2 October 2009

Keywords:
Cost structure
DEA models
Efficiency
Wastewater
Water reuse
Benchmarking methodology

ABSTRACT

In light of the growing importance of water reuse as an alternative source of water resources in many regional areas, the objective of this paper is to analyse the efficiency of wastewater treatment plants as a basic requisite to improve the potential of the water reuse. The analytical benchmarking methodology *Data Envelopment Analysis* (DEA) is used to calculate efficiency measurements. An efficiency index is obtained for each plant by means of mathematical programming techniques, aiming to minimise the inputs used in the water treatment process. This indicator is used as a reference to analyse plants' activity through a series of variables including the size of the plant or its cost structure. Given the importance of wastewater treatment in the Valencia Region (Spain), empirical research has been carried out for 338 plants located in this area. We verify the fact that the largest plants run more efficiently than smaller plants, as was to be expected. At the same time, there is evidence that a series of representative variables in the treatment process are clearly linked to efficiency. Maintenance and waste management costs are the most important factors to explain the differences between plants in terms of efficiency. Finally, the benchmarking methodology (Data Envelopment Analysis) is confirmed as a very useful management tool for the study of wastewater sector.

1. Introduction

It is common knowledge that water reuse is beneficial, not only because it enables water resources to be recovered, but also because it reduces environmental impacts. However, it is also true that some variables such as cost efficiency of the treatment process, the effluent quality and the risk existence, among others, condition its use, particularly in comparison to other available resources. In this sense, an in-depth analysis of the local water market is required in order to know the real possibilities to make water reuse an attractive option for a given sector, such as agriculture, industry and aquifer recharging. This analysis should bear in mind both the costs involved in the various water supply alternatives [1] and the type of crop, profit margins, social stance with respect to the environment, irrigation methods and guaranteeing supply, among other aspects.

Any given analysis of the potential of water reuse in a particular region and for a series of specific uses requires an extensive knowledge of the wastewater treatment processes from technical and cost point of view [2–7]. A classification of the effluents depending of their respective quality parameters enables the most suitable water treatment technology for each potential use.

Moreover, a growing use of reclaimed water for irrigation could allow a transfer of freshwater up to now used for agricultural purposes to human and industrial consumption. This would be a redistribution of available water resources in accordance with the quality required by each use and with a favourable effect on the environment. Farm crops would have a no conventional water resource of which supply would be guaranteed, even during droughts, and which would be sufficiently of high quality. This replacement of resources would occur at the same time as irrigation infrastructure was improved and, therefore, farms would use water more efficiently.

This paper focuses on analysing efficiency in wastewater treatment processes. Efficient performance, both in technical and cost terms favours water reuse possibilities and, therefore, increases the supply of the so-called non-conventional resources. Empirical research is carried out for Spain (the Valencia Region) using an analytical benchmarking methodology known as Data Envelopment Analysis (DEA).

2. Methodology

As far as a productive economy is concerned, the term efficiency is associated to the rational use of available resources. In other words, it is used to describe the optimal use of all the production factors in a production process, in accordance with the existing technology. Farrell [8] becomes the pioneer in the research of frontier functions used as references to obtain efficiency measurements for each productive unit. This method of analysis represents the beginning of what is known in

---

* Corresponding author.
E-mail addresses: Francesc.Hernandez@uv.es (F. Hernández-Sancho), Ramon.Sala@uv.es (R. Sala-Garrido).

0011-9164/$ – see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.desal.2009.01.029

economic literature as Data Envelopment Analysis (DEA). The model proposed by Farrell constructs a frontier or benchmark of the *best practice* made up of the most efficient units in the sample. This is obtained by means of linear programming techniques and assumes constant returns to scale and strong disposability in inputs. This concept means that an input may be increased without any cost in terms of increases in the rest of inputs, to maintain the level of output constant. Therefore, when a firm obtains maximum output given a certain input vector, or uses minimum inputs to produce a certain output, it will be on the so-called production frontier. In this last case, the technical efficiency of a firm can be measured by calculating the maximum possible proportional reduction in the use of factors that are compatible with its output level. For more explanation, see [9–13].

Despite the widespread presence in the literature of empirical research based on efficiency analysis, contributions in the field of the environment and more specifically in the area of wastewater management remain scarce. Practically the existing papers have concentrated on either analysing changes in the productivity of a series of plants related to water in the urban environment [14], or covering the impact of privatisation and regulation processes on the water industry in terms of efficiency [15–17], or analysing water efficiency at regional level [18] and also, on the efficiency of water price fixing [19].

This paper seeks to tackle the efficiency of wastewater treatment processes with the aim of obtaining vital information for valuing the potential of water reuse, particularly in terms of costs. In this context, efficiency is associated with the minimum use of resources (inputs) to reach a determined production (output), in accordance with existing technology. In order to achieve this, we assume a treatment process in which from a vector of inputs x we can obtain a vector of outputs y, by using an available technology.

Given that $k=1,2,\ldots,K$ plants each of them uses a vector $\boldsymbol{x}^k=(x_1^k, x_2^k,\ldots, x_N^k)$ of N inputs to carry out the production of a vector of M outputs $\boldsymbol{y}^k=(y_1^k, y_2^k,\ldots, y_M^k)$, being $\boldsymbol{z}_k=(z_1, z_2,\ldots, z_K)$ a vector of variable intensity. A specific plant of the sample is represented as k'. We can define a measure of input efficiency $E_I\,(x^{k'}, y^{k'})$ as the capacity of a plant k' to achieve an established output (contaminants removed) using the minimum of inputs (cost of energy, labour, maintenance, etc.). In other words, as each plant's vector of outputs is considered to be given, the aim is to ascertain as to what extent the vector of inputs for each of them can be minimised. Efficiency would mean that reducing the quantity of these inputs is impossible, while inefficiency would imply more possibilities of minimising them. The methodology to calculate this efficiency measure for each plant k' is widely used in the literature (see [12]) and it requires solving the following optimization problem by means of linear programming.

$$\begin{aligned}
&Min\,\lambda\\
&\text{s.t.}\\
&\sum_{k=1}^{K} z_k y_m^k \geq y_m^{k'} \quad m=1,\ldots,M\\
&\sum_{k=1}^{K} z_k x_n^k \leq \lambda x_n^{k'} \quad n=1,\ldots,N\\
&z_k \geq 0,\; k=1,\ldots,K
\end{aligned} \tag{1}$$

The measure of efficiency $E_I\,(x^{k'}, y^{k'})=\lambda$, is bounded between 0 and 1. Concretely, if

$\lambda=1$, means that the plant (k') will be considered efficient whereas, $0\leq\lambda<1$, symbolizes that the plant (k') is inefficient.

The efficiency will be decreasing when the value of an index comes closer to zero. The difference between the index λ and the value 1, can be considered as the potential reduction in inputs to obtain the same output. This methodology is empirically applied to a sample of wastewater plants, which are described in the following section.

3. Sample and variables

The sample in this paper consists of 338 Wastewater Treatment Plants (WWTP) located in the Valencia Region (Spain). All plants use the same technology of treatment known as *Secondary treatment*. Each WWTP carries out a similar process characterised by the presence of an *output*, *contaminants removed* (y_1) and five *inputs*: *energy cost* (x_1), *labour cost* (x_2), *maintenance cost* (x_3), *waste management cost* (x_4) and *other costs* (x_5). The output is the sum of contaminants [suspended solids (SS), chemical oxygen demand (COD) and biochemical oxygen demand (BOD)] removed (kilograms by year, in mean). It has been obtained by difference between influent and effluent in terms of (SS, COD and BOD). The variable other costs includes the costs for chemicals and the amortization of capital costs. These variables are described in Table 1. The statistical information comes from the *Entitat de Sanejament d'Aigües* (*EPSAR*) (*Generalitat Valenciana*) and belongs to 2004 [20].

4. Results

This involves solving the exercise of mathematical programming (1) where $k=1,2,\ldots, 338$ plants that each uses a vector $\boldsymbol{x}^k=(x_1^k, x_2^k, x_3^k, x_4^k, x_5^k)$ of inputs to obtain a vector of *outputs* $\boldsymbol{y}^k=(y_1^k)$, being $\boldsymbol{z}_k=(z_1, z_2,\ldots, z_{338})$. The results obtained from the 338 optimisation programmes (one per plant) give a mean value of 0.4187 in terms of input efficiency, which means that the sample of plants under study could save 58% overall on inputs (difference between the index value and 1) while still obtain the same output. In Fig. 1 we can see the plants (index equal 1) which make up the efficient frontier or benchmark of the best practice in relation to the inefficient plants. Fig. 2 shows the groups of the wastewater plants according to the efficiency index of each one. It is important to comment that the efficient plants (index equal 1) are only 26 (7.7% of total sample), whereas the nearly efficient plants (index between 0.8 and 1) are 23, the 6.8% of the total. Most of the plants (71.9%) have a significant inefficiency (index lower than 0.5). This result sufficiently justifies the need to carry out an in-depth analysis of each wastewater treatment plant's operations.

To explain in more detail the meaning of an efficient and inefficient performance we compare the indexes corresponding to two plants, for example, the numbers 4 and 5 of the sample. The first one is considered efficient while the second is very inefficient. In Table 2 is described the activity of these plants in terms of their inputs and output and some illustrative ratios. As it is shown, the plant number 4 obtains a bigger output by input unit used in all the cases. These results contribute to explain the important distance existing between both plants in terms of efficiency.

Once the efficiency indexes have been obtained, we aim to assess the possible relationships between this efficiency measurement in input and the size of the plant, expressed in terms of the volume of wastewater treated.

In order to achieve this, a *second stage* analysis is undertaken. From among the few options the literature provides, we use the Kruskal–Wallis test (the non parametric equivalent of the Variance Analysis of one factor) (see [21–23]) as the most suited to our objective. This entails ascertaining whether or not there are significant differences in the mean

Table 1
Sample description (338 treatment plants).

Variable	Description	Units	Annual mean
y_1	Contaminants removed	kg	362,083.06
x_1	Energy cost	Euros	30,349.33
x_2	Labour cost	Euros	56,104.49
x_3	Maintenance cost	Euros	13,350.95
x_4	Waste management cost	Euros	23,147.74
x_5	Other costs	Euros	57,109.11