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Research article

Comparing the dynamic performance of wastewater treatment systems: A metafrontier Malmquist productivity index approach

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ABSTRACT

The assessment of productivity change of wastewater treatment plants (WWTPs) is essential to improve the performance over time of the facilities evaluated. This study assessed and compared the productivity growth of WWTPs operating with non-homogeneous technologies. The metafrontier Malmquist productivity index (MMPI) was computed for a sample of 99 WWTPs encompassing 4 alternative technologies: activated sludge (AS), aerated lagoon (AL), trickling filter (TF) and rotating biological contactor (BD). The results indicated that, on average, WWTPs with AS and BD exhibited better performance over time than WWTPs with AL and TF. The MMPI indicates that, over the period 2007–2009, the productivity rose by 0.9% and 0.3% for AS and BD technologies, respectively, whilst for the AL and TF processes, the productivity decreased by 0.5% and 2.2%, respectively. The decomposition of the MMPI into efficiency change (EC) and technical change (TC) illustrated that EC was a positive driver of productivity change for WWTPs that use AS, whilst TC contributed positively to the productivity growth of WWTPs using AL and BD. Several policy implications to help managers make informed decisions were drawn from our empirical analysis.

1. Introduction

The development and assessment of wastewater treatment technologies (WWTTs) is not a novel issue. Since the beginning of the twentieth century, many WWTTs have been developed to prevent the discharge of pollutants that would cause negative environmental impacts. The interest in developing and implementing WWTTs increased with the adoption of national and international regulations aimed to minimize the impact of wastewater on the receiving water bodies (Corominas et al., 2013). Hence, a significant number of studies have been carried out to develop performance indicators for wastewater services. Most publications have focused on assessing the efficiency of pollutants' removal by both consolidated and novel WWTTs (for example: Machon et al., 2007; Garfí et al., 2012; Hudnell et al., 2011). However, both technical and economic criteria should be analyzed when evaluating the viability of a given WWTT (Benedetti et al., 2010a; Molinos-Senante et al., 2013).

From a productive perspective, a wastewater treatment plant (WWTP) can be considered as a firm that produces outputs (pollutants removed from wastewater) using inputs (operational and maintenance costs). By adopting this definition of a WWTP, the assessment of the efficiency of WWTPs is a key tool to save operational costs (Molinos-Senante et al., 2014b). Hence, recent studies have integrated technical and economic issues to assess the efficiency of WWTPs (for example: Hsiao and Yang, 2007; Benedetti et al., 2010b; Mahmoudi et al., 2012). Efficiency assessment involves comparing WWTP performance with respect to its main competitors. Hence, it is very useful for comparing the performance of WWTPs since it provides quantitative information on the WWTPs evaluated at a given moment in time (Hernández-Sancho et al., 2011). One important limitation of efficiency assessment is that it does not measure changes in the performance of WWTPs

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that have occurred over a period of time. On the other hand, the assessment of the productivity change of WWTPs is a dynamic benchmarking procedure since it evaluates how the firms are doing over time. Productivity improvement is essential to improve the competitiveness of any economic sector, including wastewater treatment. Despite the importance of this topic from a managerial and policy perspective, to the best of our knowledge, only Hernández-Sancho et al. (2011) and Molinos-Senante et al. (in press) assessed the productivity growth of a sample of Spanish WWTPs. In doing so, they computed the Malmquist productivity index (MPI) and the Malmquist-Luenberger productivity index (MLPI), respectively. The main difference between both indexes is that the MLPI integrates in the assessment not only inputs and outputs but also undesirable outputs generated in the productivity process such are greenhouse gas emissions or sewage sludge.

The MPI has been used in many applications to compare the productivity growth of different units. This direct comparison assumes that units have similar characteristics, that is, they have access to the same production technology (Zhang and Choi, 2013). In other words, the MPI assumes that units are comparable because they face the same production frontier (Chen and Yang, 2011). However, the productivity change of units that operate under a given production technology cannot be directly compared with that of units operating under different technologies. Hence, the conventional MPI cannot be used to make a direct comparison of units operating under different technologies (Latruffe et al., 2012).

In order to solve the incomparability of performances for different technologies, Hayami (1969) introduced the concept of the metafrontier function. The metafrontier is considered as an envelopment of all the possible frontiers that might arise from heterogeneous units (Wang et al., 2013). Battese et al. (2004) proposed a framework for a metafrontier production function model. Subsequently, O'Donnell et al. (2008) extended the concept of the metafrontier to the domain of measuring the change dynamics of productivity and proposed the metafrontier Malmquist productivity index (MMPI). Hence, to compare the productivity change of units operating under different technologies, the MMPI must be computed rather than the conventional MPI (Chen, 2012).

In the framework of WWTTs, Sala-Garrido et al. (2011) were pioneers in addressing the comparability of the efficiency of WWTPs that use different technologies as secondary treatment. Their study proved that to compare the efficiency of different WWTTs, the concept of a metafrontier is needed. In this sense, Sala-Garrido et al. (2011) assessed and compared the efficiency of four WWTTs through a metafrontier data envelopment analysis (DEA) model. An interesting study would be to extend this efficiency comparison of WWTTs by incorporating the temporal component, that is, to perform a dynamic analysis rather than a static one.

The limitation of the paper by Hernández-Sancho et al. (2011) is that the productivity change of a sample of WWTPs was compared directly ignoring the technology of the facilities. In other words, they assumed that the technology of the WWTPs does not affect to the productivity growth. On the other hand, Sala-Garrido et al. (2011) compared the performance of WWTPs taken into account the effect of the technology. However, their study was focused on the evaluation of the efficiency, i.e. it was a static study which did not integrate the time component.

To overcome the limitations of the previous studies (Hernández-Sancho et al., 2011; Sala-Garrido et al., 2011), the main objective of this paper is to assess and compare the dynamics of productivity growth rated for WWTTs over time. In doing so, we apply both the conventional MPI and the MMPI to a sample of Spanish WWTPs embracing four WWTTs, namely activated sludge (AS), aerated lagoon (AL), trickling filter (TF) and rotating biological contactor or biodisk (BD). Both the MPI and the MMPI are decomposed into two components: efficiency change (EC) and technical change (TC). Hence, the main factor driving productivity change over time is identified. This information is fundamental for both (waste)water authorities and WWTPs' managers to improve the productivity of WWTPs. In addition, the concept of technological gap ratio change (TGRC) is used to evaluate whether the computation of the MPI involves an under- or overestimation of the productivity change of WWTPs.

This manuscript contributes to the current strand of literature by evaluating and comparing the productivity growth of a sample of WWTPs taken into account their secondary treatment. It should be highlighted that in spite that some previous studies have evaluated the performance of WWTPs, none of them used the MMPI to compare the productivity change of these facilities over time. Hence, this study provides a pioneering and novel approach to compare the performance of WWTPs using different secondary technologies. Moreover, this study provides also insight into the drivers contributing to productivity change of WWTPs.

The methodology and results of this study are of great interest to researchers, (waste)water authorities and WWTP operators. Quantitatively assessing and comparing the productivity of WWTPs provides valuable information for selecting the most appropriate WWTT. Moreover, the identification of productivity change drivers is essential to designing and implementing measures to improve the productivity of WWTPs. This issue is vital to ensure the technical and financial sustainability of WWTPs over time.

2. Material and methods

To calculate both the groups' frontiers and the metafrontier, there are two main approaches, namely parametric and non-parametric. The parametric approach is based on the computation of a stochastic frontier, while DEA is the most widely applied non-parametric method. Despite DEA being sensitive to extreme values and to outliers, it is more attractive than parametric techniques due to its advantages, such as not setting the specific functional form of the production technology and not requiring input/output price information as well as its capability to handle the modeling of multiple inputs and outputs (Wang et al., 2013; Huang et al., in press). Hence, in this study, the DEA method was used to estimate the distance functions to compute the GMPI and MMPI.

2.1. Malmquist productivity index

Since the pioneering works of Caves et al. (1982) and Färe et al. (1994), the MPI has been widely used in many empirical studies to compute productivity change. Let us assume that DMUs use input vector $x_t \in \Re_+^M$ to produce an output vector $y_t \in \Re_+^L$ in time t and $t = 1, 2, \ldots, T$. Suppose that there are K technology sets in total and $k = 1, 2, \ldots, K$. The technologically feasible input–output combinations can be expressed in a technology set $P_t^k(x)$:

$$P_t^k(x) = \left\{ y_t^k \text{ is obtained from } x_t^k \right\} \quad (1)$$

The output-oriented distance function of this group k is defined as:

$$D_t^k\left(x_t^k, y_t^k\right) = \inf_{\delta} \left\{ \delta > 0 : \left(\frac{y_t^k}{\delta}\right) \in P_t^k(x) \right. \quad (2)$$

According to Caves et al. (1982) and Färe et al. (1994), the MPI for a DMU belonging to group k regarding period t as the base year is measured as: