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Comparing the efficiency of wastewater treatment technologies through a DEA metafrontier model

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ABSTRACT

The assessment of economic and technical efficiency is a useful tool to select the most appropriate technology for wastewater treatment. However, traditional models require that the units being assessed operate with the same technology. To overcome this limitation, we investigate the viability of using a non-concave metafrontier approach that is based on data envelopment analysis (DEA) to calculate the techno-economic efficiency and technological gap ratios (TGRs) of wastewater treatment plants (WWTPs) operating with non-homogeneous technologies. The model is applied to a sample of 99 Spanish WWTPs, encompassing four alternative technologies: activated sludge; aerated lagoon; trickling filter; and rotating biological contactor. The results indicate that mean efficiencies are relatively high and uniform across the different technologies. Furthermore, analysis of TGR values shows that techno-economic efficiency is optimal for WWTPs operating with activated sludge in comparison with the other technologies. Our study shows the importance of quantitatively comparing the efficiency of WWTPs that use different technologies in order to help managers make informed decisions when selecting the most appropriate technology.

1. Introduction

The implementation of Directive 91/271/EEC, concerning urban wastewater treatment, has resulted in a significant increase in the volume of treated wastewater by the Member States of the European Union. Thus, the percentage[2] of the population connected to wastewater treatment plants (WWTPs) has increased from 67% in 1990 to 87% in 2005 [1]. While this directive delineates the minimum quality requirements for treated water, the type of treatment processes are not defined. Following the establishment of the first wastewater treatment plants in the UK almost a century ago (by E. Ardern and T. Lockett in the UK in 1914), many technologies have been developed to produce treated water that meets legislative requirements and causes the lowest impact when discharged into the environment. Examples include: activated sludge; aerated lagoon; trickling filter; and rotating biological contactor [2].

There are several tools for selecting the most suitable type of wastewater treatment process. The information provided by these tools may be integrated in a multi-criteria decision analysis (MCDA) that facilitates decision-making when there are diverse opinions and values expressed from a variety of stakeholders. In the framework of sustainability, one of the most accepted tools is life cycle assessment (LCA) as it enables the estimation of the cumulative environmental impacts from all stages of the life cycle of a product or process [3]. LCA provides a more accurate picture of the true environmental trade-offs in technology or process selection. Despite the valuable information provided by LCA studies in the field of wastewater treatment [4,5], the tool is difficult to use in the decision making process since it requires detailed inventory data and is technically complicated [6]. Feasibility studies are also a useful tool for selecting the type of wastewater treatment that meets the needs defined by environmental legislation [7,8]. A WWTP may be considered as a firm that carries out a productive process in which the outputs are the pollutants removed from wastewater and the input is the operational and maintenance cost of the facility.

Both technical and economic criteria should be evaluated when assessing the viability of a given technology [9]. However, most studies focus on evaluating the efficiency of pollutant removal from different wastewater treatment technologies (for example: Chen et al. [10]; Baeza et al. [11]; Maine et al. [12]; Zhou et al. [13]; Xue et al. [14]), while studies on economic efficiency-related aspects are scarce (see Mufioz et al. [15]; Oa et al. [16]; Galleti and Landon [17]; Benedetti et al. [18]; Molinos-Senante et al. [19]). In contrast, recent studies have used data envelopment analysis (DEA)

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[2] Only countries with data from (almost) all the stated periods (1990–2005) are included; not all EU countries are considered.

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as an alternative approach to simultaneously assess both the technical and economic efficiency of wastewater treatment facilities (pig-farming in Taiwan [20] and urban WWPTs in Spain [21]). The two main advantages of DEA are that it can easily handle multiple output/input situations, even when they are expressed in different units, and that it can aggregate performance indicators into a single performance index.

However, the DEA technique assumes that facilities have similar characteristics [22] when the efficiency across WWTPs is assessed. This assumption is based on the argument that traditional production frontier models should not be used to compare the efficiency of firms from different technologies [23]. One possible solution is to estimate a production frontier for each studied technology and only make efficiency comparisons within each technology [24]. One study calculates separate production frontiers for two wastewater treatment technologies (activated sludge and extended aeration) to assess which is most affected by seasonal pollutant loads. However, this approach does not resolve the problem of the comparability of efficiency scores, because the efficiency levels that were measured relative to one frontier (e.g., activated sludge frontier) could not be compared with efficiency levels measured relative to another frontier (e.g., extended aeration frontier) [25].

Metafrontier analysis is an approach that allows comparison between different technologies [26–28]. The attractive feature of the metafrontier model is that it takes into account any heterogeneity between firms (in this study, WWTPs) in the comparison of efficiency [29]. A metafrontier may be considered as an umbrella (upper or lower) of all possible frontiers that might arise as a result of heterogeneity between firms [30]. This model therefore produces the maximum output from a given input using the best technology. Since its introduction, the metafrontier function has been used in a wide range of studies covering diverse topics, including: agriculture [25,31–33]; hotels [34]; football players [35]; airports [36]; banking markets [23,37,38]; hospitals [29] and dairy farms [39,40]. The reviewed literature demonstrates that the metafrontier approach is a well-established tool for evaluating efficiency analysis in non-homogeneous firms. Therefore, this approach may provide a solution to the problem of comparing techno-economic efficiency of WWTPs operating under different technologies.

This manuscript contributes to the current strand of literature in several directions. It provides efficiency scores for a sample of WWTPs and so helps identify best practices and optimize resource-use. These findings provide WWTPs operators and policy-makers with meaningful information for cost containment and reduction. To our knowledge, this paper also presents the first techno-economic efficiency comparison of different wastewater treatment technologies. Such a comparison enables the prediction of the maximum output feasible for each WWTP given the input vector.

In this study, we apply the metafrontier model to compare the techno-economic efficiency of four technologies that are used for wastewater treatment: namely activated sludge (AS); aerated lagoon (AL); trickling filter (TF); and rotating biological contactor or biodisk (BD). In addition, we use the concept of the technological gap ratio (TGR) to predict the maximum feasible output for each WWTP given the input vector. Quantitatively comparing the efficiency of WWTPs that use different technologies helps managers to make informed decisions when selecting the most appropriate technology for wastewater treatment.

The paper is organized as follows. Section 2 sets out the non-concave metafrontier and TGR concepts, and provides a short explanation of the DEA as the underlying technique for implementing the proposed metafrontier approach. Section 3 describes the main characteristics and data of the four compared technologies. Section 4 presents and discusses the results, and Section 5 summarizes key findings as conclusions.

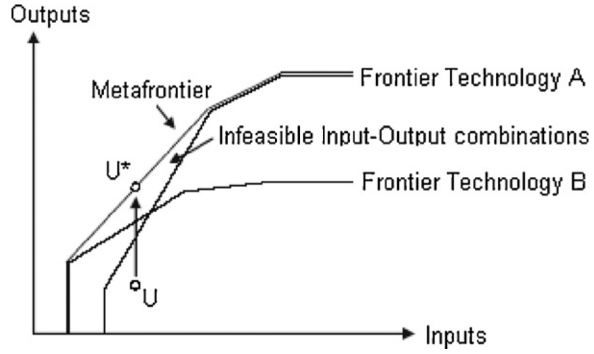

Fig. 1. Concave metafrontier.
Adapted from Tiedemann et al. [35].

2. Materials and methods

Several technologies exist for wastewater treatment, each characterized by a different functional relationship between inputs and outputs. Therefore, it is not possible to compare the techno-economic efficiency of a sample of WWTPs directly when different technologies are being used.

Production frontiers may be estimated using two types of approaches: (i) stochastic methods (for example Battese and Rao [27]; Battese et al. [28] Boshrabadi et al. [31]; Chen and Song [32]; Assaf [36]; Wang and Rungsuriyawiboon [33]); and (ii) non-parametric and non-stochastic approaches (O'Donnell et al. [25]; Zibaei et al. [39]; Kontolaimou and Tsekouras [38]; Assaf et al. [34]). The non-parametric method offers a large degree of flexibility and eliminates specification errors, as it is not necessary to select a specific functional form [41]. Because of these advantages, we have adopted this approach in our empirical evaluation.

When using both parametric and non-parametric methods for metafrontier calculation, all published studies have pooled the data across all production technologies. In this way, a concave metafrontier is obtained as shown in Fig. 1.

By performing two separate DEA efficiency analyses, the curves in Fig. 1 (labeled Technology A and Technology B) are obtained and represent technology-specific best practice frontiers. The all-encompassing metafrontier is obtained by pooling the data from the two technologies and repeating a standard DEA. However, as indicated in the works of O'Donell et al. [25] and Tiedemann et al. [35], the metafrontier may also encompass input/output combinations that are not feasible in either technology. These points are located in the triangle labeled by Tiedemann et al. [35] as 'infeasible input–output combinations' (Fig. 1). For example, consider that unit U operates under technology B. Its projected metafrontier output is represented by point U*; however an input/output combination with unit U cannot be achieved as technology A, or as technology B. The fact that U* is within the triangle termed 'infeasible input–output combinations' indicates that, although this combination is encompassed by the metafrontier, it falls outside the feasible production set.

To solve this problem, Tiedemann et al. [35] proposed an alternative method, which was based on the concept of the non-concave metafrontier. In theory, this metafrontier only envelopes the input–output combinations that are part of the delineated technology set of at least one of the technologies. As a result, the area identified as 'infeasible input–output combinations' is no longer present, as shown in Fig. 2.

For the example shown in Fig. 2, the estimation of the non-concave metafrontier involves two stages. In the first stage, the technical efficiency scores are estimated for each of the units being studied in relation to the efficient production frontier technology to which they belong. Thus, if unit U belongs to technology B then the

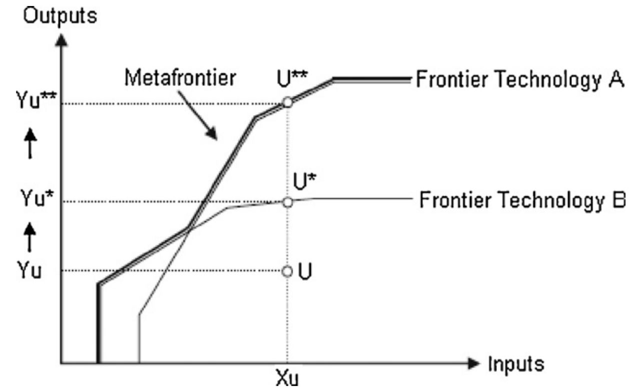

Fig. 2. Non-concave metafrontier.
Adapted from Tiedemann et al. [35].

ratio of distance $\overline{XuU}$ to distance $\overline{XuU*}$ reflects the output-oriented efficiency score in its own technology. In the second stage, we estimate the efficiency score of unit U in relation to the frontier of an alternative technology (technology A). This efficiency index is determined by the ratio of distance $\overline{XuU}$ to distance $\overline{XuU**}$. If the efficiency score using the alternative technology (technology A) is lower than that obtained for the technology to which the unit belongs (technology B), this result would indicate that when the level of inputs are constant, the unit evaluated may produce more output operating under an alternative technology. This form of comparative analysis allows us to identify the technology that represents the metafrontier at input levels around *Xu*. This same procedure may be applied to cases where more than two technologies exist that serve a similar purpose. If there are *k* different technologies ($k = 1, \ldots, K$), efficiency scores are computed for each unit against the specific frontiers for all *k* technologies.

Based on how the factors of production (inputs) are combined to obtain a set of products (outputs), DEA models can be characterized by demonstrating constant or variable (increasing or decreasing) returns to scale. If outputs increase in the same proportional change as inputs, then there are constant returns to scale. If outputs increase in a higher percentage than inputs, then there are decreasing returns to scale. If outputs increase by more than that proportional change in inputs, increasing returns to scale are revealed. Based on the previous work of Hernández-Sancho and Sala-Garrido [21], it is known that the operation and maintenance costs of WWTPs are affected by economies of scale since these authors demonstrate that larger plants run more efficiently than smaller plants. Therefore, it was considered that a DEA model based upon the assumption of variable returns to scale is the most appropriate model to apply.

To estimate the efficiency scores with respect to the metafrontier (TE) and with respect to group k (TE^k) technology, the following linear programming problem must be solved for each WWTP that is evaluated:

$$
\begin{aligned}
&\underset{\phi,\lambda}{Max} \quad \phi \\
&s.t. \\
&\sum_{j=1}^{n} \lambda_j x_{ij} \le x_{io} \qquad i = 1, \ldots, m \\
&\sum_{j=1}^{n} \lambda_j y_{rj} \ge \phi\, y_{ro} \quad r = 1, \ldots, s \\
&\sum_{j=1}^{n} \lambda_j = 1 \\
&\lambda_j \ge 0 \qquad\qquad\quad j = 1, \ldots, n
\end{aligned}
\tag{1}
$$

where variables x_{ij} and y_{rj} represent the quantity of inputs ($i = 1, \ldots, m$) and outputs ($r = 1, \ldots, s$) for each WWTP ($j = 1, \ldots, n$). The objective function of this optimization problem requires maximization of the output enhancement potential ϕ across all outputs. The reciprocal $1/\phi$ is bounded by an interval of 0–1, and may be interpreted as an efficiency score. For example, TE = 0.5 indicates that the output vector, y_r, is 50% of the maximum output that could be produced by a WWTP using the vector, x_i. If TE^k is 0.8, this represents 80% of the maximum output that could be produced by a WWTP using the input vector, x_i, and group-k technology.

The technical efficiency for each group (TE^k) cannot process a value that is below the technical efficiency with respect to the metatechnology (TE), since the restrictions of the problems of the different groups are subsets of the constraints of the metafrontier problem. In other words, the metafrontier envelops the group-k frontier. Whenever strict inequality is observed between the group-k distance function and the distance to the metafrontier function, we obtain a measure of the proximity of the group-k frontier to the metafrontier [42]. Specifically, the TGR for group-k firms (or WWTPs in our study) was defined by Battese et al. [28] as:

$$
\mathrm{TGR}^k = \frac{\mathrm{TE}}{\mathrm{TE}^k} \tag{2}
$$

Assuming that TE is 0.5 and TE^k is 0.8, the TGR would be 0.625. This means that, given the input vector (cost), the maximum output (efficiency at removing pollutants) that could be produced by a WWTP from group-k is 62.5% of the output that is feasible when using the metafrontier as a benchmark. Thus, an increase in the TGR implies a decrease in the gap between the group frontier and the metafrontier.

Hence, in this study we use the non-concave metafrontier model developed by Tiedemann et al. [35] to compare the techno-economic efficiency of a sample of WWTPs that operate under four different technologies. In addition, the technological gap between each group-k technology and its metafrontier is calculated.

3. Case study

3.1. Description of wastewater treatment technologies

Pollutants in wastewater are removed by physical, chemical and/or biological processes. These processes are grouped together to provide various levels of treatment known as preliminary, primary, secondary (with or without nutrient removal), and tertiary treatment.

The preliminary treatment removes gross solids and grit, the presence of which may damage equipment. In primary treatment, a physical operation, sedimentation is usually used to remove the floating and settleable materials found in wastewater. In secondary treatment, biological processes remove organic matter and nutrients. In conventional secondary treatments, only nutrients associated with the growth of micro-organisms responsible for the degradation of organic matter are removed. In comparison, in secondary treatments that involve nutrient removal, the operating conditions of reactors are modified to include the removal of nitrogen and/or phosphorus. In tertiary treatment, high quality effluent is obtained by removing pathogens and substances that were not previously eliminated.

WWTPs generally share common preliminary and primary treatments while differing in secondary treatments. Hence, different technologies for wastewater treatment are based on differences in secondary treatment types. Each of the technologies that are discussed in this paper is briefly described below; including activated sludge (AS), aerated lagoon (AL), trickling filter (TF), and rotating biological contactor or biodisk (BD).

Table 1
Sample description of wastewater treatment technologies. Activated sludge (AS), aerated lagoon (AL), trickling filter (TF) and biodisk (BD).

	AS	AL	TF	BD
Number of WWTPs	68	12	10	9
Volume (m^3/year)				
Mean	142,957	115,887	102,006	48,678
Std. dev.	95,369	77,829	94,243	39,096
Outputs (kg/year)				
COD				
Mean	468	548	588	579
Std. dev.	251	352	369	251
N				
Mean	32	31	25	22
Std. dev.	15	17	15	12
P				
Mean	5	4	5	3
Std. dev.	2	2	3	2
Inputs (€/m^3)				
Cost				
Mean	0.578	0.392	0.644	0.977
Std. dev.	0.419	0.213	0.517	0.713

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AS and AL treatments are suspended growth processes, in which the microorganisms used for the treatment process are maintained in liquid suspension. In comparison, TF and BD treatments are attached growth processes, in which microorganisms are attached to an inserted packing material.

The basic AS treatment process comprises three basic components: (i) a reactor, in which the microorganisms used for treatment are kept in suspension and aerated; (ii) the separation of liquid-solids, usually in a sedimentation tank; and (iii) a recycling system for returning solids that were removed from the liquid-solids separation unit to the reactor.

An AL treatment process takes place in a pond that is 1 to 4 meters in depth, in which there is a continuous flow of wastewater. The concentration of solids in the lagoon is much lower than that used in AS treatment processes, and the fundamental difference between the two processes is that sludge recirculation is not present in the AL process.

TF treatment processes are non-submerged fixed-film biological reactors, using rock or plastic packing over which wastewater is distributed continuously. Treatment occurs as the liquid flows over the attached biofilm, and wastewater is distributed above the bed by a rotary distributor. The collected liquid is transferred to a sedimentation tank, where the solids are separated from the treated wastewater.

A BD treatment process consists of a plastic disc mounted on a long, horizontal, rotating shaft. Biological slime, similar to that of the trickling filter, is attached to the filter media. However, rather than being stationary, the filter media rotates into the settled wastewater, and then emerges into the atmosphere where the microorganisms receive oxygen that facilitates the consumption of organic materials in the wastewater.

3.2. Description of the WWTPs

In this study, the four technologies under comparison mainly differ in the type of biological reactor used by WWTPs to remove organic matter and nutrients. This is because all the studied technologies require a secondary settling process for the sedimentation of suspended solids, such as separating the solids from the liquid fraction. Hence, it is considered that three pollutants are removed as a result of wastewater treatment: including (i) organic matter, which is measured as chemical oxygen demand (COD); (ii) nitrogen (N); and (iii) phosphorus (P). These three contaminants constitute the outputs obtained from the treatment process, while the operation and maintenance cost of the facilities is the input to this process. The volume of wastewater treated has not been included in the assessment of techno-economic efficiency because it was previously confirmed that the WWTPs included in our sample were not affected by the scale factor. Details of these variables for each of the four technologies are provided in Table 1.

In total, 99 WWTPs located in the region of Catalonia (northeastern Spain) were evaluated. All selected units had secondary treatment processes with nutrient removal. The wastewater that was treated at these facilities primarily originated from domestic discharges. The volume of uncontrolled toxic discharges in the biological processes is very limited, causing minimal impact to the efficiency of the facilities.

Statistical information for 2009 was supplied by the regional wastewater treatment authority (Agència Catalana de lĭAigua-ACA).

4. Results and discussion

Before estimating the metafrontier, it was first necessary to validate whether the observed differences between the four technologies was statistically significant. The Kruskal–Wallis nonparametric test was selected [43] due to non-normal distribution of the analyzed variables. This test is an extension of the Mann–Whitney *U*-test for three or more groups. The hypothesis to compare the groups is as follows:

$$\begin{cases} H_0 = k \ \text{ samples from the same population.} \\ H_1 = \text{some samples from other populations.} \end{cases}$$

Based on this test, if we obtain a level of statistical significance (p) greater than 0.05, we accept the null hypothesis and, therefore, the samples tested are not significantly different from each other, but similar. If, instead, a p value that is smaller or equal to 0.05 is obtained, then the hypothesis is rejected and we conclude that the samples are significantly different.

Table 2
Kruskal–Wallis test statistics for differences in the four wastewater treatment technologies.

	Chi-squared	*p* Value
COD	8.511	0.037
N	12.897	0.005
P	23.060	0.000
Cost	14.757	0.002

Table 3
DEA estimates of technical efficiencies (TE^k and TE) and technological gap ratios (TGR) of four WWTPs technologies: activated sludge (AS), aerated lagoon (AL), trickling filter (TF) and biodisk (BD).

WWTP technology	Mean	Std. dev.	Minimum	Maximum	WWTPs efficient (%)
AS					
TE^k	0.878	0.116	0.556	1.000	11.8
TE	0.877	0.116	0.548	1.000	11.8
TGR	0.999	0.002	0.987	1.000	
AL					
TE^k	0.954	0.061	0.843	1.000	41.7
TE	0.879	0.069	0.763	1.000	8.33
TGR	0.921	0.030	0.887	1.000	
TF					
TE^k	0.912	0.093	0.729	1.000	40.0
TE	0.812	0.064	0.651	1.000	10.0
TGR	0.882	0.108	0.618	1.000	
BD					
TE^k	0.957	0.072	0.777	1.000	56.0
TE	0.905	0.073	0.756	1.000	10.0
TGR	0.947	0.034	0.914	1.000	

Specifically, four Kruskal–Wallis tests have been carried out, one for each variable (COD, N, P, and costs) studied. Because the p value is smaller than 0.05 in all cases (see Table 2), it is demonstrated that the differences in all the variables among the four groups are statistically significant. This finding also supports the theory that a single production frontier cannot be used to compare the efficiency of WWTPs that use different technologies.

After validating that the four groups of WWTPs operate under different technological frontiers, the technical efficiency was estimated with respect to the group frontiers and to the metafrontier for each of the 99 WWTPs. All results were obtained using Eq. (1). Table 3 provides the descriptive statistics for these estimates.

We first explain and discuss the efficiency scores obtained with respect to the group frontiers. If we focus on the percentage of efficient plants, i.e. those that constitute best practices within the technology, our results indicate that there are important differences for the four types of analyzed technologies. The BD process has the highest percentage of efficient plants given that over half of the studied plants (56%) had an efficiency score equal to one. In contrast, just 12% of WWTPs using the AS process were efficient. In other words, 88% of plants that used AS secondary treatment processes could remove more pollutants with the same level of inputs. In comparison, plants using AL and TF processes exhibit an intermediate performance since the percentage of facilities operating on the frontier is 41.7% and 40.0%, respectively. Table 3 shows that the average technical efficiency scores for the studied technologies range between a minimum of 0.878 (AS technology) and a maximum of 0.957 (BD technology). These results indicate that the mean technical efficiencies are relatively uniform for the different technologies in the estimated group frontier models, and that the WWTPs examined in this study have a high efficiency within their respective technologies. For example, the mean technical efficiency score for AL technology is 0.954, indicating output is increasing by about 95% of potential – given the group frontier. In other words, the technical efficiency score shows that the mean gap between the best producer and other producers in AL technology is only about 5%. Table 3 also shows that AL, TF, and BD technologies display low variation in the obtained efficiency scores, indicating a high degree of homogeneity within each group. In contrast, WWTPs using AS technology are characterized by the highest degree of performance variability, implying a high degree of heterogeneity. This outcome was expected because the AS technology group has a larger number of plants than the other studied technologies, resulting in higher variability for both outputs and inputs for this technology, as shown in Table 1.

The efficiency of the four wastewater treatment technologies was compared by analyzing the efficiency scores with respect to the metafrontier, as shown in Table 3. As expected, we found that for all technologies the efficiency scores are smaller and more dispersed than those calculated based on the individual frontiers. This result is shown in Fig. 3, which presents a graphical illustration of the group-k and metafrontier efficiency of all WWTPs evaluated in our study.[3] In addition, we found that when techno-economic efficiency is calculated using the metafrontier as a reference point, the number of efficient WWTPs also decreases. However, this reduction in efficiency does not affect all technologies equally. For instance, the number of efficient plants using the AS process remains constant, while the number of efficient facilities is reduced by 80%, 75%, and 82% for plants that use AL, TF, and BD processes, respectively. Our results show that BD technology continues to obtain the highest mean technical efficiency (0.905). However, the lowest mean score was no longer associated with the AS process, being replaced by the TF process (0.812). This result highlights the importance of model specifications for WWTPs operating under different technology frontiers. The average techno-economic efficiency across all technologies was 0.873, which indicates that the output vector was 87.3% of the maximum output that could be produced on average by WWTPs using current inputs. In other words, the relative measurement of efficiency indicates that, when using the same input level, the WWTPs evaluated in the current study would be able to produce on average about 12.7% more output if operating on the metafrontier.

The frontier and metafrontier production estimates for each technology may also be used to calculate the technological gap ratios (TGR) by using Eq. (2). TGR measures the proximity of the group-k frontier to the metafrontier, which represents the current state of knowledge. According to Eq. (2), an increase in the TGR implies a decrease in the gap between the group frontier and the metafrontier.

Table 3 shows that the average TGR values vary from 0.882 to 0.999. Specifically, AS technology has the highest TGR, in which the average value was very close to the unitary value (i.e. the maximum value). In fact, only one of the 68 WWTPs studied with this technology presents a TGR different to one, as shown in Fig. 3. This means that, given the input vector, these plants are producing the maximum feasible output. Conversely, TF technology had a lower

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[3] The difference between Figs. 1 and 3 should be noted. In Fig. 1, the metafrontier is the upper bound, because the score ϕ of Eq. (1) has been used. In Fig. 3, the metafrontier is the lower bound because the scores belong to the form $1/\phi$ to ensure that the values are delimited between 0 and 1.

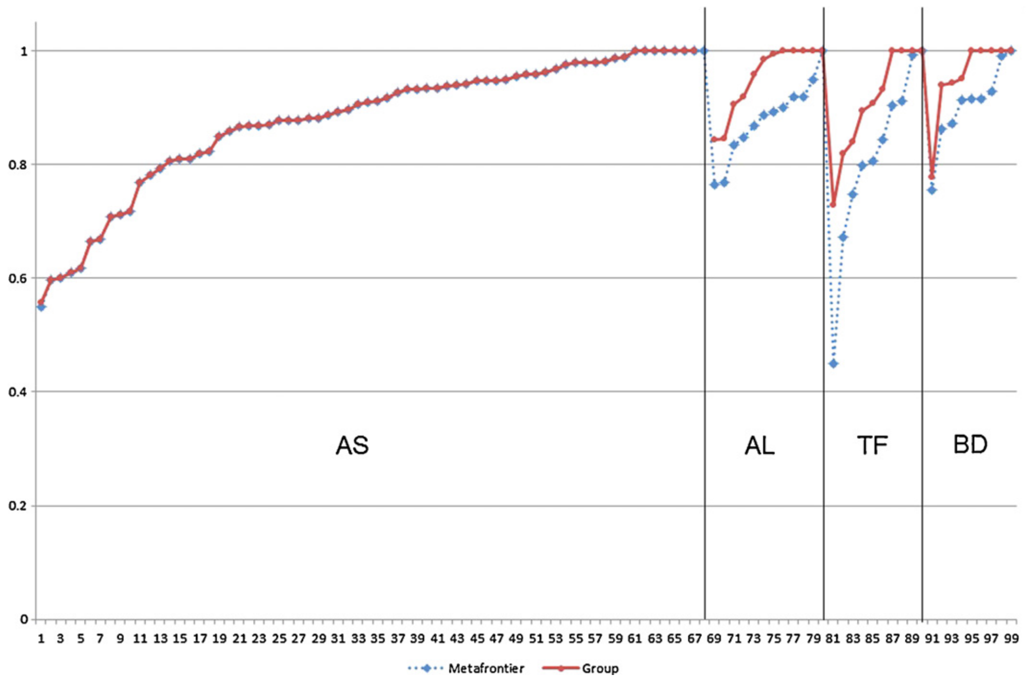

Fig. 3. Group-*k* and metafrontier technical efficiency of the 99 WWTPs grouped in four technologies: activated sludge (AS), aerated lagoon (AL), trickling filter (TF) and biodisk (BD).

TGR value (0.882), indicating that WWTPs with this technology are on average producing 88.2% of their potential output. For all technologies, the mean TGR value is 0.971, which indicates that the potential for improvement is estimated at 3% on average. The results indicate that WWTPs using AS technology have the best technical efficiency performance compared with the other technologies under study, followed by the plants using BD and AL technology. In addition, our empirical analysis shows that TF technology is the least appropriate with respect to techno-economic efficiency.

Our results are consistent with those expected and provide quantitative support that AS technology (which is a biomass system with sludge recirculation) offers high operational flexibility with respect to organic load and hydraulic variations. This flexibility arises because it is possible to modify the microbial population through a purge control of the wastewater process. Furthermore, in this technology, internal recirculation from the aerobic to anoxic reactor increases the efficiency of nitrogen removal, which then reduces the need for aeration and promotes the elimination of phosphorus [44]. Moreover, AS technology has been in operation for almost a century, hence the know-how acquired by operators also contributes to this technology being defined as best practice. This status is evidenced by the recommendations of environmental departments of the Spanish government and the wastewater treatment companies that have returned to this technology after using attached growth processes in recent decades. Specifically, the regional Programme of Urban Wastewater Treatment for Catalonia [45] 2006–2014 includes the construction of new facilities that are mostly based on this technology. However, in cases with severe restrictions regarding effluent quality or space, alternative innovative technologies with higher operating costs are also being introduced. For example, membrane bioreactors provide a small footprint alternative to conventional biological treatment methods, producing a high-quality effluent at high organic loading rates [46]. Microfiltration or reverse osmosis are processes required to regenerate the effluent from a conventional biological treatment when the water is to be reused [47].

5. Conclusions

In the current study, we provided an application of a metafrontier model, using DEA and performance data, to obtain comparable efficiency scores for Spanish WWTPs operating under four different technologies (activated sludge, aeration lagoon, trickling filter and rotating biological contactor). The results of our study indicate that the average techno-economic efficiencies are relatively uniform across all four technologies, regardless of whether the frontier or the metafrontier of each group is used as the reference (benchmark). Moreover, the average efficiency scores of all technologies were high, meaning that there is a small margin for improvement in the sampled WWTPs. At the individual level, the low variation in the recorded efficiency scores of WWTPs using AL, TF, and BD technologies show them to be homogeneous groups, while WWTPs using AS technology are characterized by greater heterogeneity. For TGR, the average value of AS technology is very close to the unitary value, which implies that plants operating this technology are producing maximum potential outputs with respect to current level of inputs. Therefore, WWTPs operating with AS technology show the best performance with respect to techno-economic efficiency compared to the other technologies evaluated in this study.

To the best of our knowledge, this work is the first application of this approach for evaluating the performance of different WWTP technologies and so provides a novel framework for identifying optimal facilities for specific regions within a country. While we suggest caution in the interpretation of the efficiency scores and TGRs, these values provide an opportunity to identify which technologies are relatively efficient. Hence, this study quantitatively supports the importance of not using the same frontier production when comparing the efficiency of WWTPs that use different types of technologies.

We recommend that wastewater companies and agencies focus on the different efficiencies of techno-economic instruments when selecting the most appropriate technology for wastewater treatment. Our study clearly demonstrates that efficiency performance is a useful quantitative tool for supporting decision-making by managers. In addition, we show the importance of using the TGR values to explain how the WWTPs of one group may compete with WWTPs from other groups. However, our interpretation of the technical efficiency scores and TGRs in the current study should be viewed as a preliminary analysis. This methodology could potentially be used as a baseline for developing an assessment of a wider range of wastewater treatment technologies. Such information would contribute towards improving our understanding of factors that affect technical efficiency and the technological gaps in wastewater processes, and provide an analysis of how technical inefficiency changes over time.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.cej.2011.08.047.

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