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Cost modelling for wastewater treatment processes

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ABSTRACT

The aim of this paper is to provide a methodology for a better understanding of the cost structure of wastewater treatment processes. This methodology may be useful in the planning of new facilities. The existing models in the literature are focused on the influence of the capacity of plant, expressed as inhabitants or flow rate, on the cost of treatment. We propose a new approach for the operating cost function that includes the most representative variables in the process. The idea is that the modelling of treatment costs enables us to understand the key role of the economies of scale in this context; and also the influence of other variables such as contaminants removed, or the age of the facility. The calculation of these extended cost functions also enables a detailed comparison to be made of the various treatment technologies from an economic point of view. In this sense, an extensive knowledge of the structure of the costs associated with each of the available treatment technologies is a basic issue in the planning of treatment processes and water reuse projects. This research applies a cost modelling methodology using statistical information from a sample of 341 wastewater treatment plants in Spain.

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1. Introduction

The need to promote the use of increasing efficient wastewater treatment technologies is generally accepted. The literature shows that many contributions have been made in this area in recent years. However, it must be remembered that the associated costs must be known in order to determine the real feasibility of any given technology [8,9]. These costs must also be understood when valuing the potential of water reuse projects [1,2,11]. Once the structure of costs is known, price fixing mechanisms should be studied to assess the demand for regenerated water. In this sense, the role of the various incentives for using water could be evaluated [10].

Any given analysis of the potential of water reuse in a particular region requires an extensive knowledge of wastewater treatment processes from an efficiency point of view. Efficient performance, both in technical and cost terms, favors water reuse; therefore, the supply of the so-called non-conventional resources increases. In the context of benchmarking methodology (data envelopment analysis), a measurement of efficiency is defined as the capacity of a wastewater treatment plant to achieve an established output (contaminants removed) using the minimum of inputs (cost of energy, labor, maintenance, etc.). For example, Hernández-Sancho and Sala-Garrido [7] apply a methodology based on the non-radial measurements of technical efficiency with the aim of calculating an efficiency indicator for each of the input used in wastewater treatment. Despite the importance of cost efficiency in the context of wastewater treatment and water reuse projects, few studies are present in the literature. The difficulty of obtaining information and the shortage of researchers working in the economic analysis of treatment processes are possible factors.

Certainly it is not easy to achieve an exhaustive knowledge of the costs associated with each treatment process nor obtain comparative figures for various technologies. However, detailed cost analysis by process is required for operating plants to make useful predictions, and for simulating new facilities.

With the aim of achieving a better understanding of the structure of operating and maintenance costs, and help in the planning of new investments, a methodology based on cost functions is proposed. These functions enable the establishment of relationships between the operation and maintenance costs — and the most representative variables in the process (such as treated volume, pollutants removed, or the age of facility). These relationships can be conjugated through a multiple regression analysis using various formulations [4–6,12].

2. Methodology

The use of cost functions is very widespread in the literature for many sectors. In the context of wastewater treatment, the first aim is to express treatment costs as a function of the treated volume of wastewater. In this sense, Sipala et al. [12] obtain the unit costs of treated wastewater for the different treatment processes, as well as several water reuse scenarios. These authors use the collected data to

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Table 1
Description of the sample, pollutant removal mean efficiency in % and standard deviation in parentheses. Source: EPSAR.

Technology	Number	Total cost (€/year)	Total volume (m^3/year)	Age (years)	Efficiency removal SS	Efficiency removal COD	Efficiency removal BOD	Efficiency removal N	Efficiency removal P
EA	193	10,082,623	29,576,995	7.1 (3.2)	90.1 (1.2)	90.6 (0.9)	94.3 (0.9)		
AS	27	13,094,371	72,369,010	7.5 (2.5)	92.9 (1.5)	90.3 (1.1)	93.4 (1.2)		
NR	58	17,662,910	71,201,719	5.5 (1.2)	91.4 (1.1)	91.4 (1.2)	91.4 (1.0)	65.4 (1.3)	63.7 (1.2)
BB	11	663,168	1,779,032	6.7 (2.0)	83.0 (0.8)	78.6 (0.9)	81.5 (1.0)		
PB	20	686,401	2,033,050	9.1 (5.3)	85.9 (1.2)	78.5 (1.5)	81.4 (1.4)		
BD	16	666,065	1,698,356	6.1 (2.2)	91.2 (0.9)	87.5 (1.2)	90.3 (1.1)		
TT	16	14,207,707	168,044,427	6.3 (1.1)	87.5 (1.4)	82.8 (1.1)	85.3 (1.3)	48.5 (0.9)	56.3 (1.0)
TOTAL	341	128,101,780	346,702,589						

develop lineal cost models as a function of capacity plant expressed as the number of equivalent inhabitants and per capita daily discharge of sewage. The formulation of the cost function is as follows:

$$Y = a - bx \tag{1}$$

where Y is the unit cost in £/m^3; x is the plant capacity in equivalent inhabitants and a, b are constant parameters.

Sipala et al. assumed that the required level of treatment and related costs could vary significantly depending on specific reuse options, regulatory requirements, and sanitary issues. As a result, a system (E.Wa.T.R.O.) was developed that could include a great variety of scenarios — and so can identify the most effective option. The cost estimations of the different treatments produced by this application represent a very useful basis for feasibility studies of water reuse projects.

In other works, more complex methodologies and formulations of cost functions have been proposed ([4], for example). The aim is always to design a tool that enables an exhaustive understanding to be obtained about the performance of the cost structure in a treatment process. These cost functions can also be used as a useful instrument for predicting the cost of a new technology, or a new facility under different scenarios. In short, the formulation that has demonstrated the best results in this context has been the potential function.

This modelling approach is applied by Gonzalez-Serrano et al. [6] to analyze the effectiveness and cost of wastewater treatment options for various uses of reclaimed water in seasonally stressed regions. The authors obtain two cost estimations, one for investment costs and another for operational and maintenance costs. The two models are used for the different levels of wastewater treatment that meet effluent quality standards corresponding to four final effluent destinations: sea outlet; surface outlet; irrigation; and aquifer recharge by infiltration or by direct injection. The investment cost function is formulated as:

$$I = AQ^n \tag{2}$$

where I is total cost of investment (€); Q is flow rate (m^3/h), while A, n are constant parameters.

In reference to the operation and maintenance cost the adjustment proposed is:

$$C = -\alpha \ln Q + \beta \tag{3}$$

where C is total cost of operation and maintenance (€/m^3); Q is also flow rate (m^3/h) and, α, β are constant parameters.

The described works are good approaches in the construction of cost functions; however, the main limitation is that the models obtained only provide information about the influence of the size of plant on the cost. To overcome this weakness, we propose a new formulation for the operating cost function that uses more explanatory variables. The idea is that by modelling treatment costs we can gain an insight into the key role of the economies of scale; as well as understand the influence of other variables — such as contaminants removed or age of facility. Also, the calculation of these cost functions enables a detailed comparison to be made among the various treatment technologies from an economic point of view. The expression obtained for our extended cost function is:

$$C = AV^b e^{\left(\sum \alpha_i x_i\right)} \tag{4}$$

or in logarithmic terms,

$$\ln C = \ln A + b \ln V + \sum \alpha_i x_i \tag{5}$$

where A, b and α are parameters; C is total cost per year; V is volume of wastewater treated per year; and the x_i are different kinds of variables representative of the treatment processes such as the age of the facility, and the efficiency removal (%) of the following contaminants removed: suspended solids (SS), chemical oxygen demand (COD), biochemical oxygen demand (BOD), nitrogen (N) and phosphorus (P).

The model parameters are obtained by ordinary least squares regression analysis, but with the additional condition that all the coefficients are positive. So a non-linear optimization model has been used in GAMS software (General Algebraic Modeling System) [3] minimizing the square of the deviation between the estimated cost through the function and the actual cost. This cost function is empirically applied to a sample of 341 wastewater treatment plants (WWTPs) shown in the following section.

3. Sample and variables

The sample used in this empirical application consists in 341 WWTPs located in the Spanish region of Valencia (on the Mediterranean coast). Table 1 shows the mean value of each variable and in parentheses its standard deviation. Statistical information has been supplied for the year 2007 by the local wastewater treatment authority (Entitat de Sanejament d'Aigües — EPSAR). The wastewater to be treated by the analyzed facilities is essentially domestic in origin and the uncontrolled dumping of toxic industrial and biological wastes are practically non-existent. Therefore, the quality of the influent of all WWTPs studied is very similar and consequently it does not affect the adjustment applied in the analysis.

A classification of the WWTP sample has been made with the purpose of obtaining a cost function for each of wastewater treatment technology. Wastewater treatment systems fall into two major categories, depending on the way in which microorganisms grow: suspended in the liquid under treatment or attached to a solid support. Extended aeration without nutrient removal (EA); activated sludge without nutrient removal (AS) and activated sludge with nutrient removal (NR) are the three types of suspension growth technologies more widely used. With respect to attached growth processes, other three technologies have been considered: Bacterial beds (BB); peat beds (PB) and biodisk (BD). WWTPs with tertiary treatment (TT) have been included in a third group since in these plants only costs associated with this stage of the process have been

Table 2
Cost functions and determination coefficient for each wastewater treatment technology.

Technology	Cost functions	R^2
EA	$C = 169.4844\ V^{0.4540}\ e^{(0.0009A + 0.6086SS)}$	0.6133
AS	$C = 2.1165\ V^{0.7128}\ e^{(0.0174A + 1.5122SS + 0.0372BOD)}$	0.6849
NR	$C = 2.518\ V^{0.7153}\ e^{(0.007A + 1.455COD + 0.258N + 0.243P)}$	0.7301
BB	$C = 17.3617\ V^{0.5771}\ e^{(0.1006A + 0.6932COD)}$	0.9862
PB	$C = 1{,}510.8400\ V^{0.2596}\ e^{(0.0171SS)}$	0.5240
BD	$C = 28.9522\ V^{0.4493}\ e^{(2.3771SS)}$	0.8058
TT	$C = 3.7732\ V^{0.7223} e^{(0.6721COD + 0.0.1958N + 0.7603P)}$	0.9029

considered. On the other technologies (suspended and attached growth) the costs include all necessary for the correct operating of the WWTP once built.

4. Results

Using operation and maintenance actual costs of the 341 WWTP object of study, costs functions have been estimated as described previously. Furthermore, in order to evaluate the variability between actual and estimated costs, both have been plotted and the determination coefficient for each cost function has been calculated. This coefficient measures the proportion of total variability of the dependent variable relative to its average, which is explained by the regression model. Its value is between 0 and 1. If the determination coefficient value is 1, the adjustment between actual and estimated data is perfect. While, if it takes the value of 0 indicates that there are no relationship between these variables. Considering this scale of values, usually an adjustment is considered acceptable when the determination coefficient value is greater than 0.5, and closer to 1 the quality of adjustment will be better.

Table 2 shows the cost functions and their determination coefficient. It is noted that all cost functions respond to a potential adjustment. Likewise, the results show that operation and maintenance costs of all technologies studied are affected by scale economies.

Where, C is total cost in €/year; V is total wastewater treated volume in m^3/year; A is the WWTP age in years; SS is suspended solid removal efficiency in %; COD is chemical oxygen demand removal efficiency in %; BOD is biological oxygen demand removal efficiency in %; N is nitrogen removal efficiency in % and P is phosphorous removal efficiency in %.

4.1. Suspended growth processes

Extended aeration (EA) and activated sludge (AS) technologies are included within suspended growth processes. The main difference between both is that EA operates with very low organic loads and high cell retention time, without primary settling. These differences in operating conditions are perfectly reflected in cost functions since results show that the constant term of the function is greater for EA than for AS, reflecting the energy cost importance of the first technology associated to the high cell retention time. Moreover, volume factor is more significant in the AS than in the EA process because this type of technology is only feasible for small populations due to requirement of a large bioreactor volume to achieve high retention time. In terms of representative variables of the process, the operating costs of both technologies are influenced by the age of the plant and SS removal efficiency. In the case of AS technology, the cost is also associated with organic matter removal efficiency.

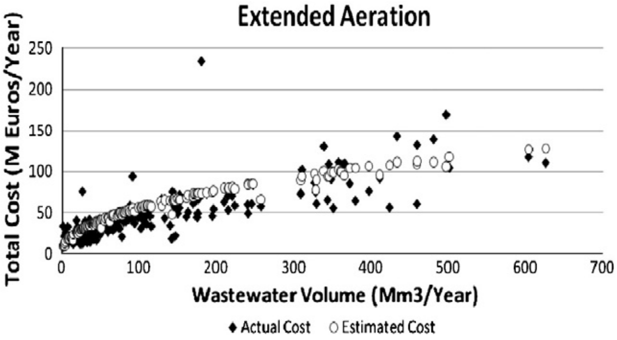

Fig. 1. Actual and estimated cost for extended aeration technology.

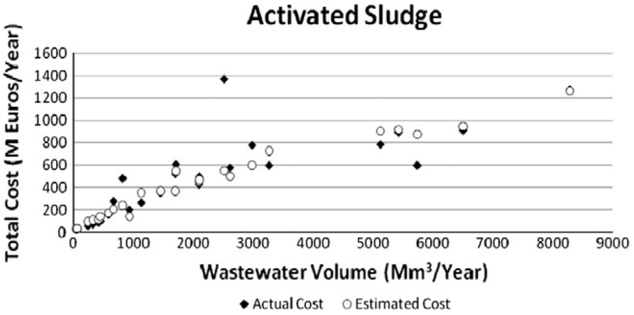

Fig. 2. Actual and estimated cost for activated sludge technology.

In relation to the technology of activated sludge with nutrient removal (NR), the estimated cost function shows that, as in the case of the AS process, the operating and maintenance costs of such plants depends largely on the size of the WWTP. Given that the aim of this technology is not only the removal of organic matter, but also the nutrient elimination, besides the age of the plant and organic matter elimination efficiency, there are other variables affecting operation costs such as nutrient removal efficiency.

With respect to the adjustment quality, we can say that is acceptable for EA and AS technologies since the value of the determination coefficient is between 0.6 and 0.7. On the other hand, the result obtained for the NR process indicates a good correspondence between the estimated and actual cost because the regression coefficient value is greater than 0.7.

Figs. 1–3 show for the three suspended growth processes (EA, AS and NR), the operating and maintenance actual costs of the WWTPs under study and the estimated costs through cost functions.

4.2. Attached growth processes

Cost functions obtained for attached growth processes reflect that scale economies play a smaller role than in the case of suspended growth technologies. This is because these facilities are more appropriate for small populations, especially in the case of peat beds (PB) as reflect the constant and the volume factor associated to the cost function of this technology.

As regards the other parameters that determine the operating and maintenance costs, the age of the plant is only significant for the

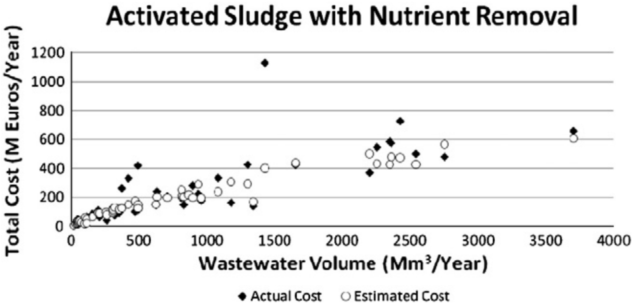

Fig. 3. Actual and estimated cost for activated sludge with nutrient removal technology.

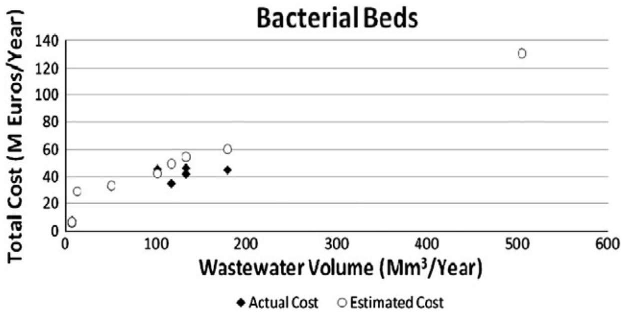

Fig. 4. Actual and estimated cost for bacterial bed technology.

bacterial bed process (BB). Biodisk (BD) and PB technologies require material replacement with more frequency and therefore plant age variable is not significant. Moreover, both in the case of PB and BD, the SS removal efficiency is considered a representative variable for determining WWTP operating costs.

The adjustment quality between actual and estimated costs for these technologies is more heterogeneous than in the case of suspended growth processes. Thus, results show that for the PB process the quality of the adjustment is poor since in this case, the determination coefficient value is 0.52. This is because the operating and maintenance costs in these type of plants do not depend only on the parameters considered in the cost function but also the operation and regeneration cycles of the peat. For the BD process, the determination coefficient value is greater than 0.8 which indicates that the correspondence between estimated and actual cost is good. Finally, the adjustment quality for the BB process is very good since the regression coefficient value is close to the unit (0.986).

Figs. 4–6 show the adjustment quality for the three attached growth technologies studied.

4.3. Tertiary treatment

This section includes various technologies such as ultrafiltration, microfiltration, membrane bioreactors and reverse osmosis. All of them are characterized because they are able to achieve pollutant removal efficiencies higher than those obtained through the technologies considered as secondary treatment. In this sense, the tertiary treatment (TT) is always preceded by the secondary treatment which may be of different typology.

For this reason, unlike suspended and attached growth processes, the overall operating costs of WWTP were not considered, but the cost function of the TT represents exclusively the costs associated with this final stage of wastewater treatment.

The obtained cost function shows that scale factor is very important for this type of technology. In relation to representative process variables, operating and maintenance costs are influenced by organic matter, nitrogen and phosphorous removal efficiencies.

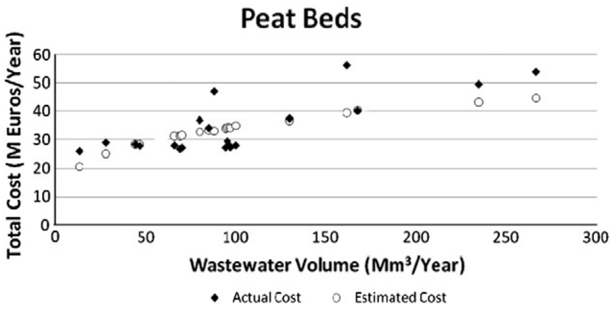

Fig. 5. Actual and estimated cost for peat bed technology.

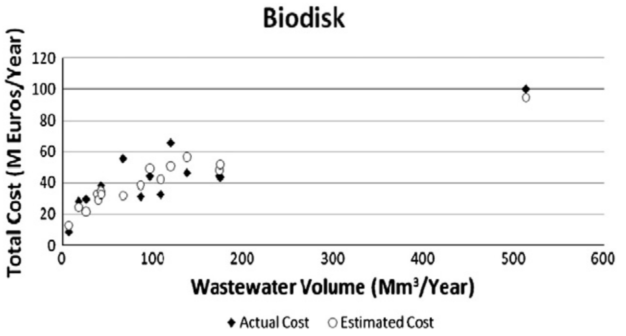

Fig. 6. Actual and estimated cost for biodisk technology.

For this technology, the correspondence between actual and estimated costs through cost function is very good since the regression coefficient value is greater than 0.9. Such correspondence is shown in Fig. 7.

5. Conclusions

Using a cost modeling methodology with statistical information from a sample of plants located in Spain, it has developed various cost functions that will enable to predict WWTP operating and maintenance costs once the value of the most representative variables in the treatment processes are known.

Cost modeling enables to increase our understanding of the operating and maintenance cost structure of WWTPs and provides a detailed and scientifically rigorous approach in the planning of new facilities, as well as assisting in evaluations of the true potential of water reuse projects. Moreover, the calculation of these functions provides valuable information in a simple way, and helps optimize the management of wastewater treatment systems. This methodology is also useful for comparing different treatment technologies from an economic point of view.

Cost functions developed show that for all technologies studied, the WWTP volume plays a very important role in the determination of the operating and maintenance costs, i.e. these costs are affected by the economies of scale. However, other variables such as plant age and pollutant removal efficiency, especially in AS, NR and TT technologies, are fundamental to explain the costs.

In the light of the results obtained in this work and, as a final conclusion we highlight that when wastewater authorities faced to the construction of new WWTPs, the criteria for selecting the most appropriate technology must not only take into account technical aspects, effluent quality requirements and investment costs but also WWTP operating and maintenance costs are very important to assess the economic feasibility of a new facility.

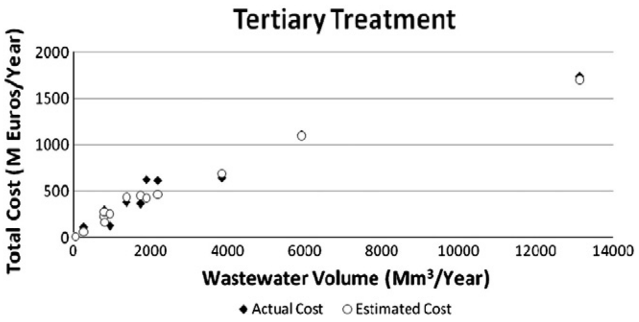

Fig. 7. Actual and estimated cost for tertiary treatment technology.

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