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Cost modeling for sludge and waste management from wastewater treatment plants: an empirical approach for Spain

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ABSTRACT

Wastewater treatment involves the generation of large volumes of sludge and other waste. Managing this waste in an economical and environmentally acceptable way has become a matter of increasing importance over the last few years. While the technologies and processes to reduce sludge generation are being widely studied, research on the economic aspects is much more limited. This study applies a cost-modeling methodology that uses statistical information from a sample of Spanish wastewater treatment plants (WWTPs) to generate a sewage sludge and waste management cost function with the aim of contributing to a better understanding of the cost structure and predicting the cost savings that will result from reducing the generation of sludge. Likewise, considering two possible scenarios, potential savings related to sludge reduction in some European countries demonstrate the helpfulness of the cost function developed.

Keywords: Cost modeling; Cost savings; Cost structure; Sludge management; Sludge minimization; Waste management

1. Introduction

The wastewater treatment process involves the generation of sewage sludge that must be managed adequately. In this context, the progressive implementation of Directive 91/271/EEC (Urban Wastewater Directive, UWWD) in all member states has increased the quantity of sewage sludge requiring disposal. In 1992, the EU produced some 5.5 million metric tons of dry matter annually. This rose to nearly 10 million tons by the end of 2010 [1]. As a result of the recent growth in sludge production, problems of storage and disposal have become more important.

According to the pollution prevention principle included in Directive 2008/98/EC, the hierarchy in sludge management states that the best option is to reduce generation, followed by reuse and recycling, and energy recovery. Landfill is the least suitable option. Therefore, the use of sewage sludge for agriculture is the most commendable alternative, since it involves the concept of recycling. The sludge is considered as a raw material with economic value [2]. Despite the potential agronomic benefits resulting from the use of sewage sludge as organic material [3],

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we must not forget that there are important limitations on the agricultural use of these residues according to the level of contaminants, especially heavy metals [4].

Along with environmental factors, economic cost is another aspect to be considered in sludge management. Sewage sludge treatment involves considerable costs, estimated at between 25 and 50% of the operating costs of wastewater treatment plants (WWTPs) [5,6]. For example, Pavan et al. [7] reported that the treatment of biowaste in Treviso WWTP was estimated to be €50 per ton. Even though the sewage sludge is used as fertilizer, the WWTP operators do not currently receive any income from its sale because there is no regulated market for it. Likewise, we must keep in mind that the sludge is not the only waste generated in WWTPs. Sand, urban waste, and fats are also removed during treatment. These residues, as well as the sludge, must be managed properly to avoid negative impacts on the environment. In this sense, and given the variety and quantity of wastes generated as a result of wastewater treatment processes, WWTP operators certainly have to assume important costs since in most cases they are responsible for direct management of them.

On one hand, the amount of sand, urban waste, and fats generated in WWTPs depends mainly on the influent characteristics and therefore is not affected by the mode in which the plant is operated. However, for sewage sludge, although the amount produced also depends on the influent quality, it is noted that depending on the cell retention time, type of sludge digestion and even the addition of chemical uncouplers or modification of the treatment process in order to alter the microbial metabolism—that is, depending on how the WWTP is operated—the amount of sludge generated can be minimized [8].

The reduction in waste generation from the wastewater treatment process is a challenge that must be addressed by both the administration and WWTP operators with a twofold purpose: firstly, to increase the sustainability of these facilities; and secondly, to reduce the operational costs. In this sense, there is a growing interest in the study of technologies and processes that enable reduction in sludge production, as evidenced by the significant number of works found in the literature related to this topic e.g. [9–11]. While the technical aspects of sludge reduction are being widely studied, contributions relating to the economic aspects are much more limited e.g. [12–14]. However, when WWTP operators are faced with the implementation of these technologies, not only the technical aspects but also the economic aspects must be considered.

Against this background, the main objective of this study is to predict the cost savings that WWTP operating companies will achieve if they make changes in operating conditions to reduce sewage sludge generation. For this task, and using a cost-modeling methodology with statistical information from a sample of WWTPs in Spain, a cost function is developed that will allow prediction of sludge and waste management costs once the quantity generated in a WWTP is known. To our knowledge, no previous contribution has developed a cost function for waste management from WWTPs. This study is therefore intended to contribute to a better understanding of the cost structure.

2. Methodology

The use of cost functions for estimating the investment or operational costs of wastewater treatment is widespread in the literature. In this context, different approaches have been developed. For example, Wen and Lee [15] applied fuzzy linear regression in an uncertain context. The cost functions developed by Gratziou et al. [16] follow the approach of analyzing the components of each system. Anagnostopoulos et al. [17] proposed a multicriteria approach based on a fuzzy extension of the analytical hierarchy process. In this context, Papadopoulos et al. [18] compared the ordinary least squares and fuzzy linear regression approaches. Nevertheless, most authors e.g. [19–24] use a statistical method to develop cost functions to predict investment and operational costs of WWTPs.

In spite of these wide contributions, to our knowledge, there is no reference to the context of waste management from WWTPs. In this study, we followed a statistical method to develop a cost function of waste management from WWTPs. The main steps from the collection of the raw data to the generation of the cost function are described as follows.

(1) *Sort through the data on the basis of technology*. Considering the purpose of this article, sorting means distinguishing between the various options for managing the sewage sludge: agricultural use, landfill, incineration, etc. In all WWTPs in the sample, the sewage sludge is used as fertilizer.
(2) *Choose a reference year for economic valuation*. Due to the difficulty in obtaining economic data relating to the operation of WWTPs, the reference year

of all available information is not always homogeneous. In this case, it is necessary to choose a reference year, which is generally the year of analysis. Fortunately, in our case study, there were enough data to develop the cost functions corresponding to a single year (2009).

(3) *Decide on the cost components that will be included in the cost functions*. Taking into account that sewage sludge, sand, urban waste, and fats are the main wastes generated from wastewater treatment, it was considered that the cost function should include these four types of waste.

(4) *Choose the functional form of the cost function*. The formulation of the cost function of sludge and waste management from WWTPs consisted in the assessment of the relationship between the dependent variable C (cost) and the independent variables X (quantity of each waste) by regression analysis. For this purpose, different models can be used. Some of them are as follows:

Inverse $C = a + \frac{b}{X}$

Logarithmic $C = a + b \ln X$

Power $C = aX^b$

Quadratic $C = a + bX + cX^2$

(5) *Adjust all available data to comply with the choices in Step 3 regarding cost components*. In cases, where a cost component is missing from the reported cost figure, it must be estimated on the basis of information from other sources. Fortunately, in our study, we did not have this problem since all defined data were available.

(6) *Having the sets of adjusted figures and using appropriate statistical methods, "best-fit" cost functions are generated*. In our study, the model parameters are obtained by ordinary least squares regression analysis, but with the additional condition that all the coefficients are positive. The Statistical Package for the Social Sciences program was used for making the adjustment. General Algebraic Modeling System software was used to obtain the cost function dependent on various variables.

3. Sample description

The sample used in this empirical application consists of 71 WWTPs located in the Spanish region of Valencia (on the Mediterranean coast). All the plants use activated sludge technology to treat the wastewater without specific processes to remove nutrients. The sludge is treated through aerobic digestion and the by-product is used for agriculture. The ultimate reason for selecting these WWTPs is that the sample was the most homogeneous available. Hence, it is important to highlight that the cost function developed here is useful in estimating the cost of sludge management in plants with similar characteristics to those utilized in this study. The statistical information comes from the Valencia

Table 1
Sample description

	Mean	Standard deviation
Sludge management cost (€/year)	69,432	5,554
Waste management cost (€/year)	79,574	7,161
Sludge (Kg wet matter /year)	2,045,236	56,536
Sand (Kg/year)	32,009	5,762
Urban waste (Kg/year)	100,040	15,008
Fat (Kg/year)	4,767	906
Volume of wastewater (m^3/year)	1,256,215	175,870
People equivalent	18,912	2,297
Old (years)	11	5
Removal efficiency of suspended solids (%)	90.5	8.4
Removal efficiency of chemical demand of oxygen (%)	88.3	7.9
Removal efficiency of nitrogen (%)	52.7	10.2
Removal efficiency of phosphorus (%)	41.2	8.4

Table 2
Components of sewage sludge

Component	Mean	Standard deviation
N (%)	4.31	2.25
P (% P_2O_2)	3.81	1.68
K (% K_2O)	0.43	0.22
Ca (% CaO)	5.92	3.19
Mg (% MgO)	0.83	0.34
Fe (mg/Kg DM)	11,886.39	10,520.79
Cd (mg/Kg DM)	1.81	0.64
Cu (mg/Kg DM)	286.39	164.67
Ni (mg/Kg DM)	25.50	20.24
Pb (mg/Kg DM)	56.67	35.29
Zn (mg/Kg DM)	829.00	268.40
Hg (mg/Kg DM)	0.94	1.11
Cr (mg/Kg DM)	41.67	30.25

wastewater management authority (Entitat de Sanejament d´Aigües—EPSAR) for the year 2009. Table 1 shows the description of variables used. Table 2 provides information about the components of the sewage sludge.

4. Results and discussion

Using statistical information for the 71 WWTPs studied, a cost function has been estimated as previously described. Furthermore, to evaluate the variability between actual and estimated costs, both have been plotted and the determination coefficient (R2) 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. A value of 0 indicates that there is no relationship between the variables. Considering this scale of values, an adjustment is usually considered acceptable when the determination coefficient value is greater than 0.5, and closer the value is to 1, the better the quality of adjustment will be.

As reported in the methodology section, there are several functional forms of the cost function. Since there are no previous references that develop the corresponding cost function in the field of waste management from wastewater treatment, as a first approach we followed the works of González-Serrano et al. [23] and Friedler and Pisanty [22]. These authors, among others, have illustrated that the best adjustment for wastewater treatment costs (water line) is the power adjustment. Taking into account the variables that should be included in our cost function, the power function for waste management is as follows:

$$C = a \times e^{(b \times S + c \times N + d \times W + g \times F)} \tag{1}$$

where C is waste management cost (€/year); S is the amount of sludge evacuated (kg wet matter/year); N is the amount of sand obtained (kg/year); W is the amount of urban waste produced (kg/year); F is the amount of fats evacuated (kg/year); and, a, b, c, d, and g are parameters.

There are two results that prevent us from accepting the hypothesis that waste management costs present a power adjustment. On the one hand, the resolution of this model showed an R^2 value of 0.66, which is not very good. On the other hand, and more importantly, only the variable S (amount of sludge evacuated) has been identified as significant. Therefore, the other wastes (sand, urban waste, and fats) did not contribute to waste management costs.

In order to overcome this limitation, two approaches were developed. The first was based on development of a power cost function, with the amount of sludge evacuated as the only variable included Eq. (2):

$$C = a \times e^{(b * S)} \tag{2}$$

The resolution of the model provided the following cost function:

$$C = 12,061 \times e^{(3E-07 \times S)} \tag{3}$$

The determination coefficient was 0.424. Hence, this model was not appropriated to explain waste management cost from WWTPs.

The second approach was based on the assumption that waste management costs depend linearly on the amounts of wastes generated. Thus, the proposed formulation is as follows:

$$C = a + b \times S + c \times N + d \times W + g \times F \tag{4}$$

The resolution of the regression model using the ordinary least squares method allows us to obtain the following cost function for waste management from WWTPs:

$$C = 0.12585 + 0.03275S + 0.00936N + 0.01245W + 0.34801F \tag{5}$$

All the coefficients are significant at 5%, and the determination coefficient is 0.8812. Hence, it has been determined that linear function provides the best adjustment.

According to our model, waste management costs are unaffected by scale economies. This is mainly because all the plants included in our model are small and do not present anaerobic digestion of the sludge. Moreover, sludge management involves operations that do not depend on the quantity of sludge generated: (i) analysis of the receiving soil in order to determine the maximum amount of sludge that can be added; (ii) analysis of the agronomic parameters; (iii) analysis of the heavy metals; and (iv) analysis of the microbiological compounds of the sludge.

The function emphasizes the importance of the fats cost management since the term associated with this waste is about 10 times higher than that corresponding to sludge management. The reason for this is that

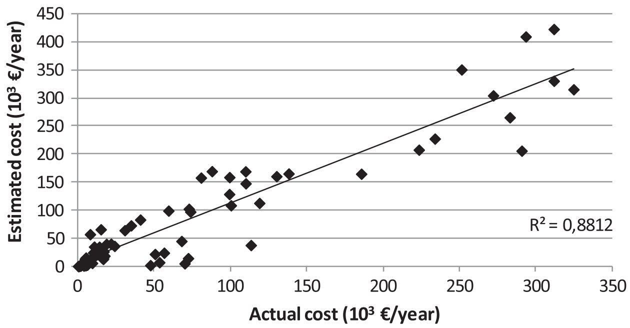

Fig. 1. Actual and estimated cost for sludge and waste management.

fats removed in the wastewater treatment process are considered hazardous waste and therefore must be managed by a licensed manager of hazardous waste external to the WWTP operator, with a consequent increase in costs. However, we can say that sand, urban waste, and fats management costs are insignificant compared to sludge management costs, as these wastes are generated in much smaller amounts (see Table 1). On the other hand, the term associated with sludge management shows that for every ton of evacuated sludge there is an increase in costs of €32.75 per year.

With respect to the adjustment quality, we can say it is good since the value of the determination coefficient is 0.8812. Fig. 1 shows the actual waste management costs of the WWTPs under study, and those estimated through the cost function. It is noted that for some WWTPs, the real cost of waste management is lower than the theoretically expected cost, while for others it is greater. These discrepancies among actual and estimated costs are associated primarily with differences in how far the sludge must be transported from the WWTP to farm land.

Aiming to show the usefulness of the cost function developed, and using as reference the data from a hypothetical WWTP, actual and estimated waste management costs have been compared. The criterion for the selection of this plant is that, in terms of waste generation, it presents similar characteristics to the mean of the entire sample. The capacity of this WWTP is about 1,200,000 m^3/year with an organic load of 27,000 population equivalent. As with all WWTPs considered in this study, the process for treating the wastewater is activated sludge without nutrient removal. The results shown in Table 3 indicate that, as can be expected taking into account the determination coefficient value of the cost function, the discrepancy between actual and estimated costs is not significant, at around 3%.

Having demonstrated the reliability of the cost function developed, the costs that operating companies could save by reducing the quantity of sludge generated have been quantified, at the European level. It is considered that the amount of other waste (sand, urban waste, and fats) remains constant since it depends on the influent characteristics. For this purpose, two possible scenarios of reduction are presented. In the first, it is assumed that the sludge reduction in relation to the current amount is 10%. while in the second it is 20%. It is worth noting that the selection of these two scenarios is not arbitrary. While some works e.g., [25–27] show that by using chemical uncouplers, the oxic-settling-anoxic process or lysis-cryptic growth, it is possible to achieve a reduction in sewage sludge generation of 30–75%, the truth is that these measures represent an additional cost for WWTP operators since they involve an investment or an increase in the operating and maintenance costs of the WWTP. However, the objective of reducing the amount of sewage sludge generated by 10–20% can be achieved through increasing the solids retention time. This approach does not involve any additional cost for WWTP operators.

According to EUROSTAT [27], the generation of sewage sludge for 29 European countries was around 52,295 million kg/year and its management costs were 1,712,661,250 €/year. Considering the waste management cost function, if the European WWTPs, due to changes in operating conditions, achieve a reduction

Table 3
Actual and estimated cost for waste management for a WWTP of 1,200,000 m^3/year capacity

	Sludge generation (Kg/year)	Sand generation (Kg/year)	Urban waste generation (Kg/year)	Fat generation (Kg/year)	Actual cost waste management (€/year)	Estimated cost waste management (€/year)	Variation (%)
Hypothetical WWTP	2,158,397	28,591	83,291	4,830	75,979	73,676	−3.0

of their sewage sludge generation by 10%, more than €171.3 million a year could be saved. For a more ambitious sludge reduction goal of 20%, such savings would amount to around €342.5 million a year. For example, in Spain the total cost of wastewater services in the year 2009 amounted to €1,700 million. Therefore, the potential savings from the reduction in the generation of sludge represent approximately 1.2 and 2.3% of the total costs for a 10 and 20% sludge reduction, respectively. In light of these results, significant cost savings can be achieved by reducing the production of excess sludge as a result of changes in WWTP operating conditions.

5. Conclusions

Because the management of sewage sludge and other waste in an environmentally acceptable way implies high economic costs, in the coming years WWTP operators will have to reduce excess sludge production. In order to predict the cost savings that WWTP operators could achieve through a reduction in sludge generation, a cost function has been developed using statistical information from a sample of WWTPs in Spain. This approach will enable prediction of sludge and waste management costs once the quantity generated in a WWTP is known.

Results show that sludge management costs are unaffected by scale economies, since the linear type formulation provides the best results. Moreover, sand, urban waste, and fats management costs are lower than sludge management costs, as these wastes are generated in much smaller amounts. Likewise, demonstrating the usefulness of this cost function, the potential savings in some European countries considering two sewage sludge reduction scenarios have been quantified.

As a final conclusion, and in light of the results obtained in this research, we emphasize the importance of reducing the amount of excess sludge produced in wastewater treatment processes, not only for environmental reasons but also to lessen the economic impact for WWTP operators.

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