Contribution of a Simple Sludge Treatment in a WWTP Optimization Procedure

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Abstract: - In the sequence of the work done with a combined ATV and double exponential model to describe the secondary settler concerning the optimal design of a wastewater treatment plant (WWTP), a simple sludge treatment based on dewatering followed by deposition in landfills is now included in the system. Power consumption, transport and deposition of the sludge are involved in the operation cost of the sludge treatment. This work aims to evaluate the contribution of this cost in the WWTP design total cost. The experiments carried out with three WWTPs in design show that the considered wasted biosolids treatment does not affect the design although is responsible for 10 to 14% of the total costs.

Key-Words: - WWTP optimal design, Secondary settler modeling, Sludge treatment, Cost function minimization

1 Introduction

Due to the high costs associated with the construction and operation of a wastewater treatment plant (WWTP), it is convenient to conduct a careful analysis of the involved models, and perform an optimization of the entire system.

Considering the performance and associated costs, the most important treatment in a WWTP is the secondary treatment. The activated sludge system composed by an aeration tank and a secondary settler is the most commonly found secondary treatment.

The most commonly found models in literature to describe the aeration tank are the ASM kind models [6, 7]. To describe the secondary settler, the ATV [2] and the double exponential (DE) [9] models have been used in the past. The ATV model is usually used as a design procedure to new WWTPs. It is based on empirical equations that were obtained by experiments and does not contain any solid balances, although it contemplates peak wet weather flow (PWWF) events. The DE model is the most widely used in simulations and it produces results very close to reality. However, as it does not provide extra sedimentation area needed during PWWF events, the resulting design has to consider the use of security factors, many times inadequate.

The optimization procedures found in the literature involving secondary settlers are based on very simple models [10] or on the ATV model [1, 3]. To the best of our knowledge, and until last year, there have been no optimization attempts using the DE model. However, simulation procedures have been made with the DE model aiming to find the best combination of the decision variables to achieve the minimum cost design, for example [8].

Recent real optimization procedures using the DE model were carried out in order to obtain the best optimal WWTP design in the sense that a minimum cost is attained. Work done in [4] goes on comparing the ATV+DE combined model with the two traditional models (ATV and DE) separately. Based on numerical experiments we were able to conclude that the combined model provided the most equilibrated WWTP design. Further, the three resulting designs were introduced in the GPS-X simulator (http://www.hydromantis.com) and some stress condition based on a PWWF value of about 5 times the normal flow was imposed. Only the combined model was able to support this adverse condition maintaining the quality of the effluent under the values imposed by the portuguese laws.

However, the above mentioned work that relies on the combined model for the secondary settler does not contemplate the sludge treatment. In fact, when the sludge leaves the secondary settler, part of it is recycled to the aeration tank and there is an excess of the sludge that has to be purged. This waste also needs a treatment. The wasted sludge in small or medium scale WWTPs is nowadays simply dewatered by highly efficient centrifuges and then incinerated or deposited in landfills.

In this work, optimization procedures were conducted, in the sense that a minimum cost design ought to be achieved, using the ASM1 equations to model the aeration tank, a combination of the ATV and DE models to describe the secondary settler and the dewatering and deposition in landfill of the

wasted sludge. The running experiments that were carried out also considered a primary treatment with 60% efficiency.

This paper is organized as follows. In Section 2 a brief description of the mathematical models related with the activated sludge system of a WWTP is presented. Section 3 describes the cost function used in our optimization procedure. Section 4 reports on the mathematical programming model and the obtained optimal designs as well as on the cost contribution of the sludge treatment in the WWTP total cost. Finally, Section 5 contains the conclusions and the ideas for future work.

2 The WWTP

A WWTP usually comprises three main treatments.

The primary treatment is a physical process and is used to remove gross solids and grease. Its efficiency is measured in terms of the Chemical Oxygen Demand (COD) reduction in the wastewater to be treated and it is known to vary from 40 to 70%. The costs associated with this treatment are considered negligible relative to the costs of the remaining units in the system.

Considering the performance and associated costs, the most important treatment in a WWTP is the secondary treatment. In the activated sludge system, composed by an aeration tank and a secondary settler, part of the sludge that is settled in the clarifier returns to the aeration tank, therefore, these two units can never be considered separately. Another part of the thickened sludge is wasted.

The third treatment is concerned with the wasted sludge. In the activated sludge system there is a continuous production of biosolids that must be wasted and treated.

In what follows, the model equations that describe the referred processes are presented.

2.1 Aeration tank

The aeration tank is where the biological reactions take place. The activated sludge model n.1, described by Henze et al. [6], is used and considers both the elimination of the carbonaceous matter and the removal of the nitrogen compounds. The tank is considered a completely stirred tank reactor (CSTR) in steady state. The balances around this unit define some of the constraints of our mathematical model. The generic equation for a mass balance around a certain system considering a CSTR is

$$\frac{Q}{V_a}\left(\xi_{in} - \xi\right) + r_\xi = \frac{d\xi}{dt} \qquad (1)$$

where Q is the flow that enters the tank, V_a is the aeration tank volume, ξ e ξ_{in} are the concentrations of the component around which the mass balances are being made inside the reactor and on entry, respectively. In a CSTR the concentration of a compound is the same at any point inside the reactor and at the effluent of that reactor. The reaction term for the compound in question, r_ξ, is obtained by the sum of the product of the stoichiometric coefficients, $\nu_{\xi j}$, with the expression of the process reaction rate, ρ_j, of the ASM1 Peterson matrix [6], $r_\xi = \sum_j \nu_{\xi j}\rho_j$.

In steady state, the accumulation term given by $d\xi / dt$ in (1) is zero, because the concentration is constant in time. A WWTP in labor for a sufficiently long period of time without significant variations can be considered at steady state. As our purpose is to make cost predictions in a long term basis it is reasonable to do so. The ASM1 model involves 8 processes incorporating 13 different components, such as the substrate, the bacteria, dissolved oxygen, among others. We refer to [3] for details.

2.2 Secondary settler

Traditionally the secondary settler is underestimated when compared with the aeration tank. However, it plays a crucial role in the activated sludge system. When the wastewater leaves the aeration tank, where the biological treatment took place, the treated water should be separated from the biological sludge, otherwise, the chemical oxygen demand would be higher than it is at the entry of the system. The most common way of achieving this purpose is by sedimentation in tanks. The optimization of the sedimentation area and depth must rely on the sludge characteristics, which in turn are related with the performance of the aeration tank. So, the operation of the biological reactor influences directly the performance of the settling tank and for that reason, one should never be considered without the other.

The ATV design procedure (Fig. 1) contemplates the peak wet weather flow events, during which there is a reduction in the sludge concentration. To turn around this problem, a certain depth is allocated to support the fluctuation of solids during these events

$$h_3 = \Delta X\, V_a \frac{DVSI}{480 A_s}. \qquad (2)$$

This way a reduction in the sedimentation area, A_s, is allowed. A compaction zone

$$h_4 = X_p \frac{DVSI}{1000}, \qquad (3)$$

where the sludge is thickened in order to achieve the convenient concentration to return to the biological reactor, also has to be contemplated and depends only on the characteristics of the sludge. *DVSI* is the diluted volumetric sludge index, ΔX is the variation of the sludge concentration inside the aeration tank in a PWWF event and X_p is the sludge concentration during a PWWF event.

A clear water zone (h_1) and a separation zone (h_2) should also be considered and are set empirically ($h_1 + h_2 = 1$, say). The depth of the settling tank, *h*, is the sum of h_1, h_2, h_3 in (2) and h_4 in (3). The sedimentation area is still related to the peak flow, Q_p, by the expression

$$\frac{Q_p}{A_s} \le 2400\left(X_p DVSI\right)^{-1.34}.$$

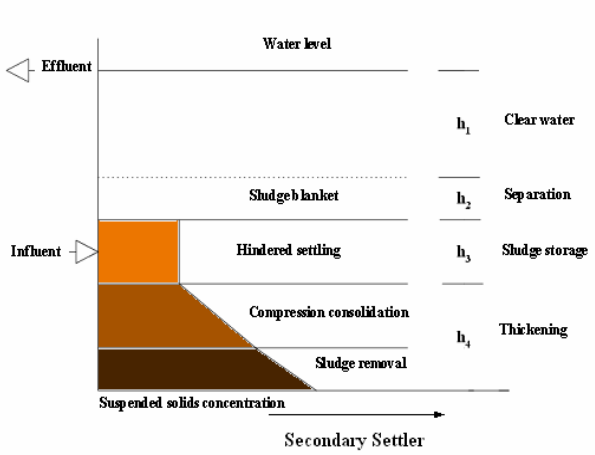

Fig. 1: Typical solids concentration-depth profile adopted by the ATV model (adapted from [2])

The double exponential model assumes a one dimensional settler, in which the tank is divided into ten layers of equal thickness (Fig. 2). Some simplifications are considered. No biological reactions take place in this tank, meaning that the dissolved matter concentration is maintained across all the layers. Only vertical flux is considered and the solids are uniformly distributed across the entire cross-sectional area of the feed layer (*j*=7, in our case). This model is based on a traditional solids flux analysis but the flux in a particular layer is limited by what can be handled by the adjacent layer. The settling function, described by Takács et al. in [9], is given by

$$v_{s,j} = \max\left(0, \min\left(v'_0, v_0\left(e^{-r_h\left(TSS_j - f_{ns}TSS_a\right)} - e^{-r_p\left(TSS_j - f_{ns}TSS_a\right)}\right)\right)\right)$$

where $v_{s,j}$ is the settling velocity in layer *j* (m/day), TSS_j is the total suspended solids concentration in each of the ten considered layers of the settler and v_0, v'_0, r_h, r_p and f_{ns} are the settling parameters. Note that $TSS_7 = TSS_a$.

The solids flux due to the bulk movement of liquid may be up or down, v_{up} and v_{dn} respectively, depending on its position relative to the feed layer, thus

$$v_{up} = \frac{Q_{ef}}{A_s} \quad \text{and} \quad v_{dn} = \frac{Q_r + Q_w}{A_s}.$$

The subscript *r* is concerned with the recycled sludge, *w* refers to the wasted sludge and *ef* refers to the treated effluent.

The sedimentation flux, J_s, for the layers under the feed layer (*j*=7,…,10) is given by

$$J_{s,j} = v_{s,j} TSS_j$$

and above the feed layer (*j*=1,…,6) the clarification flux, J_{clar}, is given by

$$J_{clar,j} = \begin{cases} v_{s,j} TSS_j & \text{if } TSS_{j+1} \le TSS_t \\ \min\left(v_{s,j} TSS_j, v_{s,j+1} TSS_{j+1}\right) & \text{otherwise,} \end{cases}$$

where TSS_t is the threshold concentration of the sludge. The resulting solids balances around each layer, considering steady state, are the following:

- for the top layer (*j*=1)

$$\frac{v_{up}\left(TSS_{j+1} - TSS_j\right) - J_{clar,j}}{h/10} = 0,$$

- for the intermediate layers above the feed layer (*j*=2,…,6)

$$\frac{v_{up}\left(TSS_{j+1} - TSS_j\right) + J_{clar,j-1} - J_{clar,j}}{h/10} = 0,$$

- for the feed layer (*j*=7)

$$\frac{\frac{Q\,TSS_a}{A_s} + J_{clar,j-1} - \left(v_{up} + v_{dn}\right)TSS_j - \min\left(J_{s,j}, J_{s,j+1}\right)}{h/10} = 0,$$

- for the intermediate layers under the feed layer (*j*=8,9)

$$\frac{v_{dn}\left(TSS_{j-1} - TSS_j\right) + \min\left(J_{s,j}, J_{s,j-1}\right) - \min\left(J_{s,j}, J_{s,j+1}\right)}{h/10} = 0,$$

- and, for the bottom layer (*j*=10)

$$\frac{v_{dn}\left(TSS_{j-1} - TSS_j\right) + \min\left(J_{s,j-1}, J_{s,j}\right)}{h/10} = 0.$$

The use of the combination of these two models to describe the secondary settler is prepared to turn around the PWWF events without over dimensioning and overcomes the limitations and powers the advantages of each one, as confirmed in our previous study [4].

2.3 Biosolids treatment

When the sludge leaves the secondary settler, part of it is recycled to the aeration tank. However there is an excess of the sludge that has to be purged. This waste also needs a treatment. In general a digestion, either aerobic or anaerobic, in order to achieve biological stabilization, followed by sedimentation or flotation and, finally dewatering is done. After this process, the resulting thickened biosolids are incinerated or deposited in landfills.

Nowadays, the process of dewatering is very efficient and is achieved by high performance centrifugation, which allows the release from the other adjacent processes.

The inclusion of the sludge treatment by dewatering and deposition does not imply additional constraints to the problem. It will however affect the total cost of the WWTP due to power consumption and transport and deposition of the sludge.

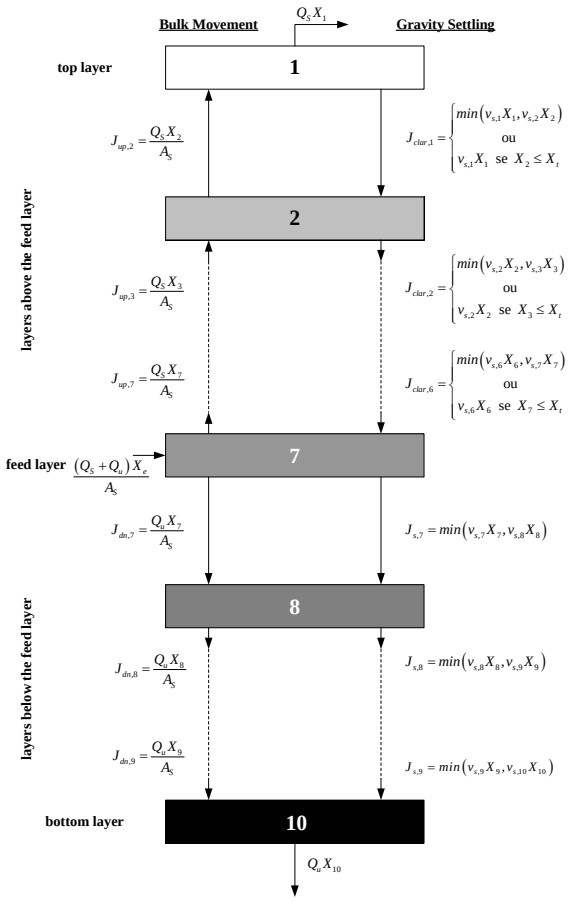

Fig. 2: Solids balance around the settler layers according to the double exponential model (adapted from [9])

2.4 Other constraints

The system behaviour, in terms of concentration and flows, may be predicted by balances. In order to achieve a consistent system, these balances must be done around the entire system and not only around each unitary process. They were done to the suspended matter, dissolved matter and flows. The equations for particulate compounds, generically represented by $X_?$, (organic and inorganic) have the following form:

$$(1+r)Q_{inf}\ X_{?ent}=Q_{inf}\ X_{?inf}+(1+r)Q_{inf}\ X_{?}-\frac{V_a\ X}{SRT\,X_{?r}}\left(X_{?r}-X_{?ef}\right)-Q_{inf}\ X_{?ef}$$

where X represents the particulate *COD*.

For the solubles ($S_?$) we have:

$$(1+r)Q_{inf}\ S_{?ent}=Q_{inf}\ S_{?inf}+r\,Q_{inf}\ S_{?}$$

where r is the recycle rate, *SRT* is the sludge retention time and $Q_?$ represents the volumetric flows. As to the subscripts, *inf* concerns the influent wastewater, *ent* the entry of the aeration tank, *r* the recycled sludge and *ef* the treated effluent.

For the flows, the resulting balances are:

$$Q=Q_{inf}+Q_r \quad \text{and} \quad Q=Q_{ef}+Q_r+Q_w.$$

An important group of constraints in the mathematical model is a set of linear equalities that define composite variables. In a real system, some state variables are, most of the time, not available for evaluation. We refer to [3] for more details.

Some system variables definitions should be added to the model in order to define the system correctly. These definitions include the sludge retention time (*SRT*), the recycle rate (r), the hydraulic retention time (*HRT*), the recycle rate in a PWWF event (r_p), the recycle flow rate in a PWWF event (Q_{r_p}) and the maximum overflow rate (Q_p/A_s). The detailed equations concerning these decision variables can be found in [3].

All the variables in the model must be nonnegative, although more restricted bounds are imposed to some of them due to operational consistencies. These conditions define a set of simple bounds on the variables. For example, the dissolved oxygen has to be always greater or equal to 2 mg/L. For details, see [3].

Finally, the quality of the effluent has to be imposed. The quality constraints are usually derived from law restrictions. The most used are related with limits in the *COD*, *N* and *TSS* at the effluent.

3 The Cost Function

The cost function is used to describe the installation and operation costs of a WWTP, in a way that reflects the behaviour of each unitary process. In the present study, the aeration tank, the secondary settler as well as the unit for the biosolids treatment are considered.

The basic structure of the cost function, based on the work done by Tyteca et al. [10], is $C=aZ^b$,

where C represents the cost and Z the variable that most influences the design of the unitary process under study.

The parameters a and b were estimated by a least squares technique considering real data collected from a portuguese WWTP building company.

At the present, the collected data come from a set of WWTPs in design, therefore no operation data are available. However, from the experience of the company, it is known that the maintenance expenses for the civil construction are around 1% during the first 10 years and around 2% in the next 10. To the electromechanical components, the maintenance expenses are negligible, but all the material is usually replaced after 10 years. The energy cost is directly related with the air flow. The power cost (P_c) in Portugal is 0.08 €/KW.h. For the sake of simplicity, no pumps were considered, which means that all the flows in the system move by the effect of gravity. Also, all the fixed costs are neglected as they do not influence the optimization procedure.

The operation cost is usually in annual basis, so it has to be updated to a present value with the parameter $\Gamma = (1+(1+i)^{-n})/i$, where i is the discount rate and n is the life span of the WWTP. The following values i=0.05 and n=20 years were used. For each unit in the system, the total cost is given by the sum of the investment (IC) and operation costs (OC).

For the aeration tank, the influent variables are the tank volume (V_a) and the air flow (G_S). The obtained investment cost is

$$IC_a = 148.6V_a^{1.07} + 7737G_S^{0.62}, \qquad (4)$$

and the operation cost is

$$OC_a = \left(0.01\Gamma + 0.02\Gamma(1+i)^{-10}\right)\left(148.6V_a^{1.07}\right) + (1+i)^{-10}\,7737G_S^{0.62} + 115.1\Gamma P_c G_S. \qquad (5)$$

In the secondary settler, the sedimentation area (A_s) and the depth (h) are the influent variables. The investment and operation costs are

$$IC_s = 955.5A_s^{0.97}, \qquad (6)$$

and

$$OC_s = \left(0.01\Gamma + 0.02\Gamma(1+i)^{-10}\right)148.6\left(A_s \times h\right)^{1.07} \qquad (7)$$

respectively.

As to the biosolids processing, the investment costs were not considered because they do not depend on the size of the WWTPs under study.

In terms of the operating cost, the power consumption by the centrifugation and the transport and final deposition of the sludge have to be considered. The annual cost obtained for power consumption is $C_P = 544.5V_a^{0.63}$.

The transport and final deposition are directly related to the amount of sludge produced, being this cost 55€/ton. In a daily basis, a volumetric flow Q_w m^3/day with a mass concentration of TSS_w g/m^3 is wasted. Thus the corresponding cost function in annual basis is $C_D = 0.02Q_wTSS_w$.

Considering the appropriate conversion to present value, the resulting operation cost due to the sludge treatment is

$$OC_{BS} = 544.4\Gamma V_a^{0.63} + 0.02\Gamma Q_w TSS_w. \qquad (8)$$

The objective function is then the sum of the cost terms (4) – (8).

4 Numerical Results

A mathematical programming problem results from the set of equalities and inequalities that relate the decision variables of the problem and were mentioned in Section 2 together with the objective function presented in Section 3.

The mathematical model has 64 parameters, 115 variables and 105 constraints, where 67 are nonlinear equalities, 37 are linear equalities and there is only one nonlinear inequality. 104 variables are bounded below and 11 are bounded below and above.

The chosen values for the stoichiometric, kinetic and operational parameters that appear in the mathematical formulation of the problems are the default values presented in the GPS-X simulator, and they are usually found in real activated sludge based plants for domestic effluents.

The problem has been coded in the AMPL mathematical programming language [5] and was solved with the software package LOQO [11], available in the NEOS Server (http://www-neos.mcs.anl.gov/).

Two sets of experiments were done in order to evaluate the importance of the inclusion of the biosolids treatment in the optimization problem. First, the cost term (8) corresponding to the wasted sludge was included in the objective function. Then the term (8) was discarded.

The goal of these numerical tests is to evaluate the percentage of the WWTP total cost that is attributed to the treatment and disposal of the wasted sludge. Three WWTPs at present in design in the North of Portugal were analyzed: Murça, Sabrosa and Sanfins. The first one of the list is slightly bigger than the other two.

Table 1 reports the optimal values of the aeration tank volume, sedimentation area, depth of the secondary settler, aeration air flow, and the design total costs (in millions of euros) for the two mentioned situations: with (*TC*+) and without (*TC*-) the biosolids treatment.

Table 1: Results for the three studied WWTPs

WWTP	V_a	A_s	h	G_S	*TC*+	*TC*-	%
Murça	1903	173	7.1	9271	6.43	5.50	14
Sabrosa	540	97.5	4.3	5588	3.96	3.56	10
Sanfins	612	108	4.4	6334	4.33	3.89	10

The obtained optimal values for V_a, A_s, h and G_S were identical in both runs, confirming that the design is not affected by the inclusion of the biosolids treatment. Only the total cost is affected. Thus, to obtain the optimal design of the units in the secondary treatment, the wasted sludge process can be left out.

Comparing the total costs, an increase due to the sludge treatment of 10 to 14% was observed in the three analyzed WWTPs (last column of Table 1). In our view, this type of variation looks significant especially because only the operation costs were considered. So, to be able to estimate the design costs the wasted biosolids treatment should be incorporated in the model.

5 Conclusions

The main conclusion from this comparative study concerning the optimization procedure is that the wasted biosolids treatment that processes the sludge only by dewatering and landfilling does not affect the design of the secondary treatment. However, it has an important contribution in the total cost of the WWTP. In particular, for large scale WWTPs, the energetic costs will become incomportable if this kind of treatment is used. To be able to reduce the sludge treatment cost, future developments will consider a different sludge treatment process, such as the sludge digestion.

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