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Biological Process Optimal Design in a Wastewater Treatment Plant

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1. Abstract
The aim of this paper is to determine the optimal design and operation of an activated sludge system that is being installed in a small town in the north of Portugal. This process design takes into consideration real data in order to define the objective cost function which includes both investment and operation costs. The collected data were also used to characterize the wastewater in that region. To define the constraints of the optimization problem, we consider very well established models for the aeration tank and the secondary settler, together with the system balances and some system definitions. The highly nonlinear optimization problem was solved through the internet by the SNOPT solver provided by the NEOS Server. We found, for the minimum cost, the optimal design/operation for the above mentioned system in terms of the volume of the aeration tank, air flow needed for the biological sludge, the sedimentation area and the secondary settler depth, to name a few of the involved variables.
2. Keywords: Process design, cost function minimization

3. Introduction
Nowadays, wastewater treatment plants (WWTP's) are a crucial concernment for the authorities. In one hand, the citizens are becoming more conscientious about the protection of the environment and, on the other hand, they must deal with the high costs associated with the installation and operation of such plants. Besides the densely populated and industrial regions, this concernment is also spreading to small country regions. In particular, we have small and poor regions in the north of Portugal that produce high quality wines and have significant effluent variations in terms of amount of pollution and flow, during the vintage season. For these reasons, it is crucial to reduce, as much as possible, the costs associated with the design and operation of WWTP's in such a way that the environmental law is accomplished.
A typical WWTP is usually defined by a primary treatment, a secondary treatment and in some cases a tertiary treatment. The primary treatment is a physical process and aims to eliminate the gross solids and grease, in order to avoid the blocking up of the secondary treatment. As its cost does not depend too much on the characteristics of the wastewater, we decided to leave it out of the optimization procedure. However, we analize and report its efficiency impact on the cost of the secondary treatment. The secondary treatment is a biological process and it is the most important treatment in the plant since it eliminates the soluble pollutants. When the wastewater is very polluted and the secondary treatment does not provide the demanded quality, a tertiary treatment, which is a chemical process can be included.
Here, we consider only the activated sludge system since this is the most common treatment process in WWTP's. This system consists of an aeration tank and a secondary settler. The influent enters the aeration tank in order to reduce the dissolved carbonaceous matter and nitrogen. The sludge that leaves this tank enters the secondary settler to remove the suspended solids. After this treatment, the treated final effluent leaves the settling tank and the thickened sludge is recycled to the aeration tank and part of it is wasted (see Figure 1).

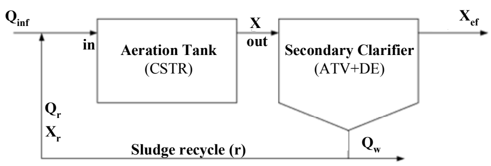

Figure 1. Schematic representation of the activated sludge system

The aim of this paper is to determine the optimal design and operation of the above mentioned process guaranteeing the water quality demanded by the portuguese law. For that matter, we use the ASM1 model to describe the biological process inside the aeration tank and a combination between the ATV and the double exponential models to the secondary settler, which together with the system balances and some system definitions define the constraints of the optimization problem. As concerns the objective, we use a cost function that represents the total cost and includes both investment and operation costs. To define it, a study based on portuguese real data was carried out with a WWTP building company and we present some results for a WWTP that is being installed in the small town of Alijó, an important wine producer in the north of Portugal.
To the best of our knowledge, apart the work done by Tyteca et al. [15], that uses simple models to describe the aeration tank and the secondary settler, no other WWTP real optimization has been published until last year. Previous published work on activated sludge systems using ASM type models [10], [11] and, either the ATV [2] or the double exponential model [14] for settling tanks, focus on obtaining the best combination of the state variables testing by simulation two or three alternative designs and choosing the one with the lowest cost [1], [9], [12], [13]. The simulations have been carried out using GPS-X (http://www.hydromantis.com), DESASS [15] or WEST$++$ (http://www.hemmis.be). Our previous work concerning WWTP optimization has been tackling different secondary settler modeling: a simple separation point with perfect clarification in [4], a simple separation point without perfect clarification in

[3] and the ATV model in [5] and [6]. Thus, the herein proposed combination of the ATV and double exponential models to describe the secondary settler is a novelty.

The resulting highly nonlinear optimization problem is coded in AMPL modeling language [7] for optimization and to solve it we resorted to the NEOS Server (http://www-neos.mcs.anl.gov/) which provides the possibility to run problems on powerful machines in a user friendly manner through the internet. From the available solvers to use with the AMPL language, we tested several, and we chose the SNOPT solver, for being the one with better performance for our problem.

We found, for the minimum cost, the optimal design and operation for the above mentioned system in terms of the volume of the aeration tank, air flow needed for the biological sludge, the sedimentation area, the secondary settler depth, the recycle rate, the effluent flow and concentration of total suspended solids, carbonaceous matter and total nitrogen in the treated water, to name a few of the involved variables.

This paper is organized as follows. In Section 4 we present a detailed description of the equations of the mathematical model. Section 5 reports on the numerical experiments done with a real WWTP and Section 6 contains the conclusions.

4. Mathematical model

The system under study is the one represented in Figure 1. To model the aeration tank we chose the activated sludge model n.1, described in [10], which considers both the elimination of the carbonaceous matter and the removal of the nitrogen compounds. For the settling tank we used a combination between the double exponential model [14] and the ATV design procedure [2]. For the aeration tank we consider a completely stirred tank reactor (CSTR) in steady state and we also assume that no biological reactions take place in the secondary settler.

4.1. Aeration tank

The mass balances done inside the aeration tank resort to the ASM1 model [10]. In what follows we describe the equations resulting from these balances. The generic equation for a mass balance around a certain system considering a CSTR is

$$\frac{Q}{V_a} = (\xi_{in} - \xi) + r_\xi = \frac{d\xi}{dt},$$

where Q is the flow that enters the tank, V_a is the aeration tank volume, ξ and ξ_i are the concentrations of the component around which the mass balances are being made inside the reactor and on entry, respectively. It is convenient to refer that 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 [10]

$$r_\xi = \sum_j \upsilon_{\xi,j} \rho_j .$$

In steady state, the accumulation term given by $\frac{d\xi}{dt}$ is zero, since 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. For example, the mass balance equation related to the soluble substrate (S_S) is the following:

$$-\frac{\mu_H}{Y_H}\frac{S_S}{K_S+S_S}\left(\frac{S_O}{K_{OH}+S_O}+\eta_g\frac{K_{OH}}{K_{OH}+S_O}\frac{S_{NO}}{K_{NO}+S_{NO}}\right)X_{BH}+k_h\frac{X_{BH}}{K_X X_{BH}+X_S}\left(\frac{S_O}{K_{OH}+S_O}+\eta_h\frac{K_{OH}}{K_{OH}+S_O}\frac{S_{NO}}{K_{NO}+S_{NO}}\right)X_S+\frac{Q}{V_a}\left(S_{S_{in}}-S_S\right)=0.$$

We denote all the soluble components by $S_?$ and the particulates by $X_?$. Similar mass balance equations appear for the slowly biodegradable substrate (X_S), the heterotrophic active biomass (X_{BH}), the autotrophic active biomass (X_{BA}), the particulate products arising from biomass decay (X_P), the nitrate and nitrite nitrogen (S_{NO}), $NH_4^+ + NH_3$ nitrogen (S_{NH}), the soluble biodegradable organic nitrogen (S_{ND}), the particulate biodegradable organic nitrogen (X_{ND}), the alkalinity (S_{alk}) and the soluble oxygen (S_O) (see [10] for details on how to obtain all the other equations). All these equations depend on stoichiometric and kinetic parameters. Table 1 lists these parameters.

Table 1. Stoichiometric and kinetic parameters used in the ASM1 model

Stoichiometric	Kinetic	
Y_A	μ_H	K_{NH}
i_{XB}	k_h	b_H
Y_H	K_S	b_A
i_{XP}	K_X	η_g
f_P	K_{OH}	K_{OA}
	μ_A	η_h
	K_{NO}	k_a

4.2. 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 (COD) 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.

To model the secondary settler we propose a combination between the ATV design procedure [2] and the double exponential model [14]. This combination was never used before. It is our conviction that the combination of the two models better resembles the ongoing biological process in the WWTP under study.

The ATV model is based on empirical equations that were obtained by experiments. This model does not contain any solid balances, however it contemplates the peak wet weather flows (PWWF). The double exponential model originally proposed by [9], is the most widely used in simulations and it produces results very close to reality. It was never used before on optimization procedures. As it does not provide the extra sedimentation area needed during PWWF events, it has to consider the use of security factors, many times inadequate.

As mentioned before, the ATV design procedure contemplates the PWWF events, during which there is a reduction in the sludge concentration. To address this issue, a certain depth, h_3, is allocated to support the fluctuation of solids during these events, allowing a reduction in the sedimentation area (A_s):

$$h_3 = \frac{0.3\,TSS_a}{1000\,V_a}\frac{DVSI}{480\,A_s}\,.$$

where $DVSI$ is the diluted volumetric sludge index and TSS_a represents the total suspended solids concentration that leaves the aeration tank. A compaction zone, h_4, 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

$$h_4 = \frac{0.7\,TSS_a}{1000}\frac{DVSI}{1000}\,.$$

A clear water zone, h_1, and a separation zone, h_2, should also be considered and we set them empirically (h_1+h_2=1, say). The depth of the settling tank, h, is the sum of these four zones. Figure 2a illustrates the distribution of the solids in the different zones of the settling tank. To describe this procedure fully, one more equation that relates the sedimentation area with the peak flow, Q_P, should be added:

$$\frac{Q_P}{A_s} = 2400\left(\frac{0.7\,TSS_a}{1000\,DVSI}\right)^{-1.34}.$$

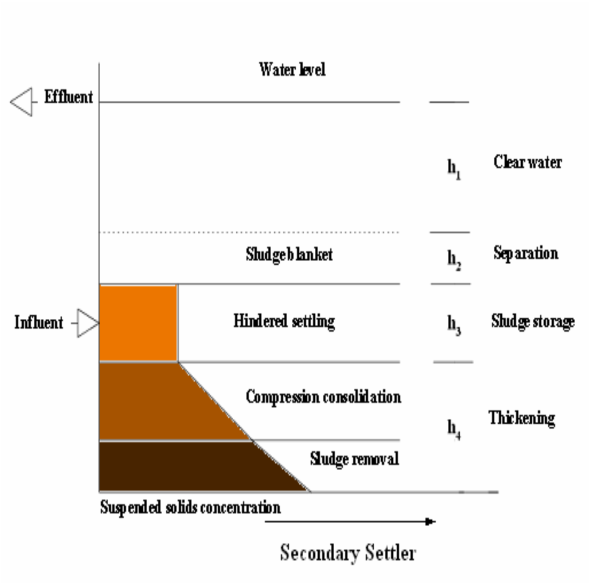

Figure 2a. Typical solids concentration-depth profile adopted by the ATV design procedure (adapted from [2])

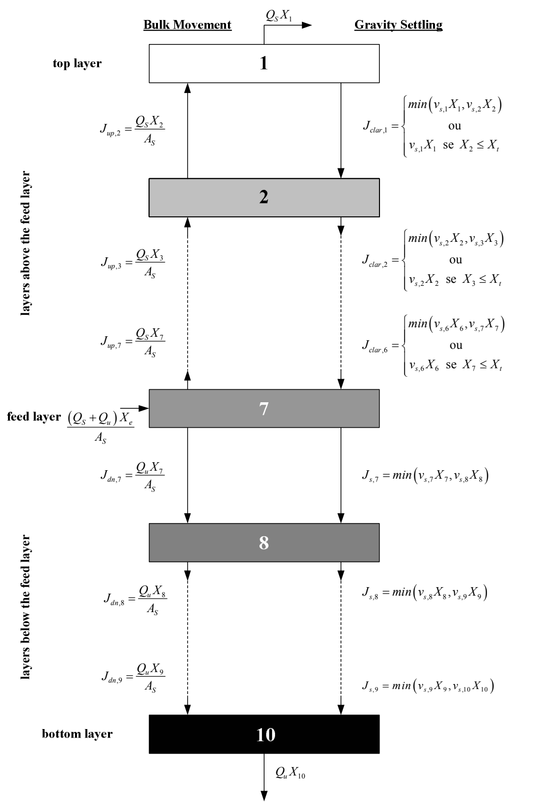

Figure 2b. Solids balance around the settler layers according to the double exponential model (adapted from [14])

The double exponential model assumes a one dimensional settler, in which the tank is divided into 10 layers of equal thickness (Figure 2b). 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 [14], is given by

$$\upsilon_{s,j} = \max\left(0, \min\left(\upsilon'_0, \upsilon_0\left(e^{-r_h(TSS_j - f_{ns}TSS_a)} - e^{-r_p(TSS_j - f_{ns}TSS_a)}\right)\right)\right).$$

where $\upsilon_{s,j}$ 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 υ_0, υ'_0, r_h, r_p and f_{ns} are settling parameters. Note that $TSS_7 = TSS_a$.
The solids flux due to the bulk movement of liquid may be up or down, υ_{up} and υ_{dn} respectively, depending on its position relative to the feed layer, thus

$$\upsilon_{up} = \frac{Q_{ef}}{A_s}$$

and

$$\upsilon_{dn} = \frac{Q_r + Q_w}{A_s}.$$

As to the subscripts, r concerns the recycled sludge, w the wasted sludge and ef the treated effluent.
The sedimentation flux, J_s, for the layers under the feed layer (j=7,…,10) is given by

$$J_{s,j} = \upsilon_{s,j} TSS_j$$

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

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

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)

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

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

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

— for the feed layer (j=7)

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

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

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

— and, for the bottom layer (j=10)

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

4.3 Other important definitions

The other important group of constraints 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. Thus, readily measured composite variables are used instead.

— The chemical oxygen demand (COD) is composed by soluble and particulate components, that are related by the equation

$$COD = X_I + X_S + X_{BH} + X_{BA} + X_P + S_I + S_S,$$

where X_I represents the inert organic suspended solids and S_I is the inert organic dissolved matter;

— the volatile suspended solids (VSS) are given by

$$VSS = \frac{X}{icv},$$

where X is the particulate component of COD and icv is a parameter that converts unit of COD in units of mass;

— The total suspended solids (TSS) are given by

$$TSS = VSS + ISS,$$

where ISS denotes the inorganic suspended solids;

— the biochemical oxygen demand (BOD) is given by

$$BOD = f_{BOD}\left(S_S + X_S + X_{BH} + X_{BA}\right),$$

where f_{BOD} is biological fraction of the substrate and biomass;

— the total nitrogen of Kjeldahl (TKN) is related to the nitrogen compounds, biomass and organic suspended matter by

$$TKN = S_{NH} + S_{ND} + X_{ND} + i_{XB}\left(X_{BH} + X_{BA}\right) + i_{XP}\left(X_P + X_I\right),$$

— and, the total nitrogen (N) is given by

$$N = TKN + S_{NO}.$$

The system behavior, 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 (organic and inorganic) have the following form

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

and, for the solubles we have

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

where r is the recycle rate and SRT is the sludge retention time. For the flows, the resulting balances are

$$Q=Q_{inf}+Q_r$$

and

$$Q=Q_{ef}+Q_r+Q_w,$$

with $Q_?$ representing the volumetric flows. As to the subscripts, *inf* concerns the influent wastewater and *ent* the entry of the aeration tank.

It is also necessary to add some system variables definitions, in order to define the system correctly. In this group, we include the sludge retention time, the recycle rate, hydraulic retention time (HRT), recycle rate in a PWWF event (r_P), recycle flow rate in a PWWF event (Qr_P) and maximum overflow rate (Q_P/A_s):

$$SRT=\frac{V_a X}{Q_w X_r},$$

$$HRT=\frac{V_a}{Q},$$

$$r=\frac{Q_r}{Q_{inf}},$$

$$r_P=\frac{0.7\,TSS}{TSS_{\max,P}-0.7TSS},$$

where $TSS_{max,P}$ is the maximum possible concentration of solids in a PWWF event,

$$Qr_P=r_P Q_P,$$

$$\frac{Q_P}{A_s}\le 2\cdot$$

A fixed value for the relation between volatile and total suspended solids was considered

$$\frac{VSS}{TSS}=0.7\cdot$$

All the variables are assumed nonnegative, although more restricted bounds are imposed to some of them due to operational consistencies:

$$0\le K_L a\le 300,$$

$$0.05\le HRT\le 2,$$

$$800\le TSS_a\le 6000,$$

$$2500\le TSS_r\le 10000,$$

$$0.5\le r\le 2,$$

$$6\le S_{alk}\le 8,$$

$$6\le S_{alk\ ent}\le 8,$$

$$S_O\ge 2,$$

$$Q_w\le 500\cdot$$

where K_La is the oxygen mass transfer coefficient.

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. In mathematical terms, these constraints are defined by the portuguese law as

$$COD_{ef}\le COD_{law},$$

$$N_{ef}\le N_{law},$$

$$TSS_{ef}\le TSS_{law}\cdot$$

4.4 Objective cost function

The cost function represents the total cost and includes both investment and operation costs. In this paper, for the sake of simplicity, no pumps were considered, which means that all the flows in the system move by the effect of gravity.

The operation cost is usually on annual basis, so it has to be updated to a present value with the updating term Γ:

$$\Gamma=\sum_{j=1}^{n}\frac{1}{\left(1+i\right)^j}=\frac{1-\left(1+i\right)^{-n}}{i},$$

where i is the discount rate and n is the life span of the WWTP. We use i=0.05 and n=20 years. The total cost is given by the sum of the investment (IC) and operation (OC) costs:

$$TC=IC+OC\,.$$

To obtain a cost function based on portuguese real data, a study was carried out with a WWTP building company. The basic structure of the model is $C=aZ^b$, where a and b are the parameters to be estimated and Z is the characteristic of the unitary process that most influences the cost. For example, for the investment cost of the aeration tank, the volume (V_a) and air flow (G_S) are considered. The parameters a and b are estimated by the least squares technique, using the collected data. The investment cost obtained for the aeration tank is

$$IC_a = 148.6\, V_a + 7737\, G_S \cdot$$

The data come from a WWTP in design, thus operation data are not available yet. However, from the company experience, the maintenance expenses for the civil construction are around 1% of the investment costs, during the first 10 years, and around 2% otherwise. For the electromechanical components, the maintenance expenses are negligible, but all the materials are 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. With this information and with the updating term Γ, the operation cost of the aeration tank is then

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

The term $(1+i)^{-10}$ is used to bring to present a future value, in this case, 10 years from now.
The settling tank was considered to operate only by gravity. Thus, the correspondent investment cost is

$$IC_s = 995.5 A_s^{0.97},$$

and for the operation cost, that only concerns the maintenance for the civil construction, we obtain

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

Finally, the total cost function is given by the sum of all the costs previously presented:

$$TC = 174.2 V_a^{1.07} + 12487 G_S^{0.62} + 114.8 G_S + 955.5 A_s^{0.97} + 41.3\left(A_s (1 + h_3 + h_4)\right)^{1.07} \cdot \tag{1}$$

5. Computational Results and Discussion

The problem of the optimal design and operation of the activated sludge system consists in finding the volume of the aeration tank, the air flow needed for the aeration tank, the sedimentation area, the secondary settler depth, the recycle rate, the effluent flow and concentration of total suspended solids, carbonaceous matter and total nitrogen in the treated water, to name a few, in such a way that, verifying the aeration tank balances as well as the system balances, satisfy the composite variables constraints, the secondary settler constraints, the system variables definition constraints, the quality constraints and the simple bounds on the variables, and minimize the cost function (1). Our formulated problem 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 problem are the default values presented in the simulator GPS-X, and they are usually found in real activated sludge based plants for domestic effluents.

The collected data from the analyzed small town Alijó are listed in Table 2. These data consider the population equivalent, the influent flow, the peak flow, the influent *COD*, the influent *TSS* and define average conditions that are crucial for the dimensioning of the plant.

Table 2. Data collected from Alijó

Pop. Eq.	influent flow (m^3/day)	peak flow (m^3/h)	*COD* (Kg/m^3)	*TSS* (Kg/m^3)
6850	1050	108	2000	750

This mathematical programming problem was coded in AMPL. AMPL [7] is a mathematical programming language that allows the codification of optimization problems in a powerful and easy to learn language. AMPL also provides an interface that allows a wide variety of solvers to communicate with it. We refer to the AMPL web page (www.ampl.com) for more details on AMPL and related solvers. Although our optimization problem is not large, it is highly nonlinear. Furthermore, the small feasible region (104 equality constraints out of 105) makes the problem difficult to solve. NEOS Server provides the possibility to run problems on powerful machines in a user friendly manner through the internet. Most of the NEOS Server nonlinear constrained optimization solvers for AMPL input format are unable to solve our problem. The SNOPT solver [8] turned out to be the most suitable for our problem. The AMPL model can be requested to the first author.

All the solver parameters were left as default. Several experiences were done for the WWTP under study. We considered different values of *COD* reduction in the preliminary treatment. This reduction typically varies from 40 to 70%. Table 3 presents the effect of the primary treatment efficiency on the cost and design of the activated sludge system for the WWTP from Alijó. In the table, we report the volume of the aeration tank, air flow, secondary settler sedimentation area and depth, *COD*, *TSS* and *N* at the effluent, total cost in present value and the number of iterations needed by SNOPT to converge to the solution.

Table 3. Results for some of the variables using the combination between the ATV and double exponential models

Efficiency (%)	V_a (m^3)	G_S (m^3/day STP)	A_s (m^2)	h (m)	*COD* (g/m^3)	*TSS* (g/m^3)	*N* (g/m^3)	Total cost (10^6 €)	Iterations
0	6300	217013	15035	1.77	108.2	5.3	0.67	65.2	3543
40	3917	124832	216.7	10.6	68.9	6.0	0.63	34.3	4178
50	3917	99721	216.7	10.6	58.9	6.0	0.64	29.0	2017
60	3917	74603	216.7	10.6	49.0	6.0	1.2	23.5	11443
70	3917	48941	216.7	10.6	43.3	6.0	1.2	17.4	1598

From Table 3 we may observe that the air flow is the most dependable variable on the primary treatment efficiency, as the aeration tank volume, the sedimentation area and depth of the secondary settler can be kept constant for different primary treatment

efficiencies. Thus, the air flow for the aeration tank directly depends on the primary treatment efficiency.
Figure 3 presents the relation between the primary treatment efficiency with the total cost of the activated sludge system, as well as the quality of the resulting effluent, measured by a quality index, QI [1], that is defined by

$$QI = \frac{Q_{ef}}{1000}\left(2TSS_{ef} + COD_{ef} + 2BOD_{ef} + 20TKN_{ef} + 20S_{NO_{ef}}\right).$$

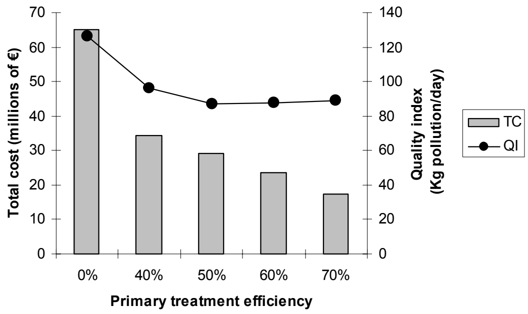

Figure 3. Total cost and quality index *versus* the primary treatment efficiency

From the graphic we can see clearly that as the efficiency of the primary treatment increases, the cost decreases and the quality of the effluent gets better. However, the most dramatic difference occurs when we pass from the situation in which there is no primary treatment to the one that we have a primary treatment with 40% of efficiency. From this point on, the differences in the total cost are not so significant, and the effluent quality is maintained for the three levels 50, 60 and 70% of the primary treatment efficiency.
As shown, the efficiency of a primary treatment is crucial because the higher is the achieved *COD* reduction, the lower are the investment and operation costs of the secondary treatment. We remark that the cost of the preliminary treatment is also related with its efficiency, although not as dramatically as the cost of the activated sludge system.
In all the presented situations, the *COD*, *N* and *TSS* law limits (125, 15 and 35, respectively) are never achieved, remaining these values always under those bounds.

6. Conclusions

In this paper we consider the optimal design and operation, in terms of minimum installation and operation costs, of an activated sludge system in a WWTP from the north of Portugal, based on real data and effluent quality law limits. A real WWTP was analyzed and the mathematical modeling of the activated sludge system was carried out using the ASM1 model for the aeration tank and a combination of the ATV and double exponential models for the settling tank, resulting in an optimization problem whose objective is to minimize the investment and operation costs, running the NEOS Server solver SNOPT.
From our numerical experiences, we may conclude that the efficiency of the primary treatment directly influences and in a very expressive way the resulting cost of the biological treatment. To have a more realistic idea of the best solution, the whole treatment plant should be considered as future developments, in order to see if the costs associated with the primary treatment would balance the observed cost differences in the secondary treatment. It is our intention to include also the sludge digestion and final disposal processes when analyzing the whole WWTP.

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