OPTIMIZATION OF WASTEWATER TREATMENT PLANT DESIGN AND OPERATION USING SIMULATION AND COST ANALYSIS

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ABSTRACT

This paper defines an objective economic index, which integrates both investment and fixed and variable operating costs of a wastewater treatment plant. The main objective is to standardize a cost calculation procedure, to be able to compare different treatment scenarios. The development of the cost criterion may be specific to each particular case, especially to assess variable operating costs.
The use of cost models and of simulation in the comparison of treatment alternatives is then illustrated through two case studies. The first simple example refers to the design phase of a plant whereas, in the second example, real time control strategies are investigated through dynamic modeling and simulation. Such investigations are likely to result in considerable savings.

KEYWORDS

Cost criteria, design, dynamic simulation, economic optimization, wastewater treatment plant

INTRODUCTION

When designing a new wastewater treatment plant (WWTP) or when upgrading an existing one, different treatment alternatives and operating strategies may be evaluated with the help of a cost index. However, software tools that have been developed to design cost-effective WWTP such as CAPDET (McGhee *et al*., 1983) or STOM (Spearing, 1987), as well as optimization studies (Tyteca, 1985; Pipyn *et al.*, 1994; Fels *et al*., 1997), suffer from two major drawbacks:

(i) the cost indices used are often restrictive: only investment or specific operating costs are considered;

(ii) the time-varying characteristics of the wastewater are not directly taken into account but through the application of large safety factors, which induce an increase in the costs. Moreover, the use of adequate operating strategies such as real-time control is rarely investigated, despite the benefits that may be achieved (Vanrolleghem *et al*., 1996; Ekster, 1998).

The first objective of this paper is to define an objective economic index derived from cost functions, including both investment and variable operating costs over the life span of a plant.
Secondly, the advantage of using simulation as well as these costs is illustrated through two recently studied applications. In the first one, the impact on the costs of the expected maximum load used for the design of an industrial plant is investigated. In the second one, a study supporting the choice between the implementation of different control strategies that optimize the polymer dosage to an overloaded clarifier is presented.

OVERALL WASTEWATER TREATMENT PLANT COST FUNCTIONS

WWTP costs are in general subdivided in investment and operating costs. The latter may be fixed (normal operation and maintenance, fixed power, …) or variable (power and chemical consumption, sludge treatment and disposal and effluent taxes). In order to assess the preliminary costs of a plant - to be able to choose between different alternatives in the early phase of a project - cost functions may be used (Wright and Woods, 1993 - 1994; Agences de l'eau, 1995; Fels *et al*., 1997).

Investment cost functions

Investment costs for major treatment plant units may be quantified as function of the process size (e.g. volume, area, flow rate) by use of power laws or polynomial functions. To estimate investment costs related to pipes or instrumentation, cost factors (percentage of the investment cost) are often applied.
Examples of investment cost functions may be found in the literature (Tyteca, 1985; Wright and Woods, 1993 - 1994; Fels *et al*., 1997). However, when only using literature data, accurate estimation

of investment costs can hardly be expected. Cost functions are indeed developed at a given time for a specific company, region or country and any extrapolation is not without risk. Moreover it is difficult to compare various relationships extracted from different sources, as the description of the components taken into account in the relationships is often poor. Finally, an indication of the accuracy obtained using literature data is rarely provided. As a result, cost analysis in the early phase of a project requires the development of specific cost functions, if accurate and reliable estimation is pursued.

Results of an investigation performed for Flanders (Vermeire, 1999) are presented in Table 1. The cost functions have been developed for a typical layout of domestic WWTPs (oxidation ditch). Investment costs are expressed in Euro of 1998 and are subdivided in construction (concrete, excavation, foundation) and electromechanical equipment (purchase and installation). Taxes, administration cost and engineering cost are not considered.

Table 1 - Investment cost functions developed for municipal WWTPs in Flanders (Vermeire, 1999)

Unit	Item	Components included	Cost function	Parameter	Parameter Range
Influent pumping station + screening	C[1]		$2334\ Q^{0,637}$	Q = flow rate (m^3/h)	250-4000
	EM[2]	Screws Screen	$2123\ Q^{0,540}$ $3090\ Q^{0,349}$		
Oxidation ditch	C	Selector, aeration tank + sludge recirculation	$10304\ V^{0,477}$	V = volume (m^3)	1100-7700
	EM	Aeration system	$8590\ OC^{0,433}$	OC = oxygen capacity (kgO_2/h)	30-630
Settler	C		$2630\ A^{0,678}$	A = area (m^2)	175-1250
	EM	Rack	$6338\ A^{0,325}$		
Sludge recirculation	EM	Screws	$5038\ Q^{0,304}$	Q	35-2340
Storage tank + Thickener	C	Buffer tank+thickener	$5559\ V^{0,473}$	V	330-1860
	EM	sludge mechanism, pumps, …	$10093\ A^{0,149}$	A	8-30
Effluent unit	EM	Venturi meter	$3350\ Q^{0,363}$	Q	125-2130
Construction			$6592\ Q^{0,498}$	Q	250-4000
Infrastructure			$3873\ Q^{0,772}$	Q	250-4000
Electricity			$16482\ Q^{0,383}$	Q	250-4000
Instrumentation			$2438\ Q^{0,351}$	Q	250-4000

[1] C = Construction

[2] EM = Electromechanical equipment

The functions presented in Table 1 have been statistically validated and they allow to estimate the total investment cost of a plant (with a similar layout) with a maximum error of 25 %.

Operating cost functions

Total operating cost may be related to global plant parameters (e.g. average flow rate, population equivalent), generally through power laws (Smeers and Tyteca, 1984; Balmér and Mattson, 1994; WERF, 1997). However, such relationships apply to the average performance of plants and often suffer from a high uncertainty, unless very similar plant configurations are considered.

In order to take into account simulation data to estimate operating costs, deductive models may be issued from engineering calculations (Brett *et al*., 1998; Jacquet, 1999). However, such development requires some skill, and on-site data collection is preferable when possible (when upgrading an existing plant), in order to check and refine the cost models or to build new (inductive) models.

Table 2 and 3 gather different cost functions that may be used to estimate fixed and variable operating costs. In order to avoid cost adjustment, non-monetary units (i.e. man-hour, kW) have been preferred when possible in the development of the cost functions (Balmér and Mattson, 1994).

Table 2 - Examples of fixed operating cost functions

Cost	Parameter	Cost function	Symbols and units	Reference
Normal operation and maintenance	Population Equivalent PE	L = Uc PE	L = labour, man-hour/y, Uc = unit cost, man-hour/y/PE	Jacquet, 1999
Clarifier mechanism	Area A (m^2)	$P = \theta A^b$	P = power, kW θ, b = constant	Fels *et al.*, 1997
Mixers	Volume V (m^3)	P = Ps.V	P = power, kW Ps = specific power, kW/m^3	Jacquet, 1999
Small equipment	Population Equivalent PE	C = Uc PE	C = cost, Euro/y Uc = unit cost, Euro/y/PE	Alexandre and Grand d'Esnon, 1998
Analyses	Population Equivalent PE	C = Uc PE	C = cost, Euro/y Uc = unit cost, Euro/y/PE	

Table 3 - Example of variable operating cost functions

Cost	Parameter	Cost functions	Symbols and units	Reference
Pumping power	Flow rate Q (m^3/s)	$P = Qwh / \eta$	P = power, kW w = specific weight of the liquid, N/m^3 h = dynamic head, m η = pump efficiency, -	ASCE, 1992
Aeration power Fine bubble aeration	Oxygen transfer coefficient K_La_f (h^{-1}) Dissolved oxygen concentration C (g/m^3)	$q_{air} = (K_La_fCsV/A\alpha\rho_{O2}y_{O2})^{1/(B+1)}$ $P = \gamma/(\gamma-1).P_1/ \eta.q_{air} . [(P_2 / P_1)^{(\gamma-1) / \gamma} - 1]$ (*see development in Appendix*)	*see Appendix*	Jacquet, 1999 *this study*
Sludge Thickening, dewatering and disposal	Excess sludge TSS (t)	Uc TSS	Uc = Unit cost, Euro/t TSS	Alexandre and Grand d'Esnon,1998 Jacquet, 1999
Chemicals Consumption	Consumption, Cn (kg)	Uc Cn	Uc = Unit cost, Euro/kg chemical	
Effluent taxes (organic matter and nutrient)	COD, BOD_5, N, P, TSS	$L=Uc (k_{org}.N_{org} + k_{nut}.N_{nut})$	Uc = Unit cost, N_{org} = f(Q, BOD, TSS, COD) N_{nut} = f(Q, N, P)	Vanrolleghem *et al.*, 1996

Cost functions given in Tables 2 and 3 only illustrate possible models in their generic form. As seen in Table 2, fixed operating costs may be related to the plant size or unit size (PE, volume, area). The assessment of variable operating costs on the basis of simulation variables and parameters requires a number of hypotheses (e.g. head losses, oxygenation efficiency, see Table 3): each particular case may thus require the development of specific cost functions.

Finally, when comparing different alternatives, special attention should be paid to the time and space scales chosen (Vanrolleghem *et al.*, 1996), as they may influence the choice of the implemented cost functions (Rivas and Ayesa, 1997). At best, an overall plant evaluation over the life span of the plant should be conducted.

Total cost of a WWTP

The total cost of a plant is often determined using the present worth method (White *et al.*, 1989). All annual operating costs for each process are converted into their corresponding present value and added to the investment cost of each process to yield the net present value. If IC_k represents the investment cost of a unit k, and OC_k the operating cost, the net present value (NPV) of a plant over a period of n years can be determined as:

$$\mathrm{NPV} = \sum_{k=1}^{N} \mathrm{IC}_k + \left(\frac{1-(1+i)^{-n}}{i} \right) \sum_{k=1}^{N} \mathrm{OC}_k \tag{1}$$

Where i is the interest rate and N is the number of units.
Results could also be expressed as equivalent annual worth (AW):

$$\mathrm{AW} = \frac{i(1+i)^n}{(1+i)^n - 1} \sum_{k=1}^{N} \mathrm{IC}_k + \sum_{k=1}^{N} \mathrm{OC}_k \tag{2}$$

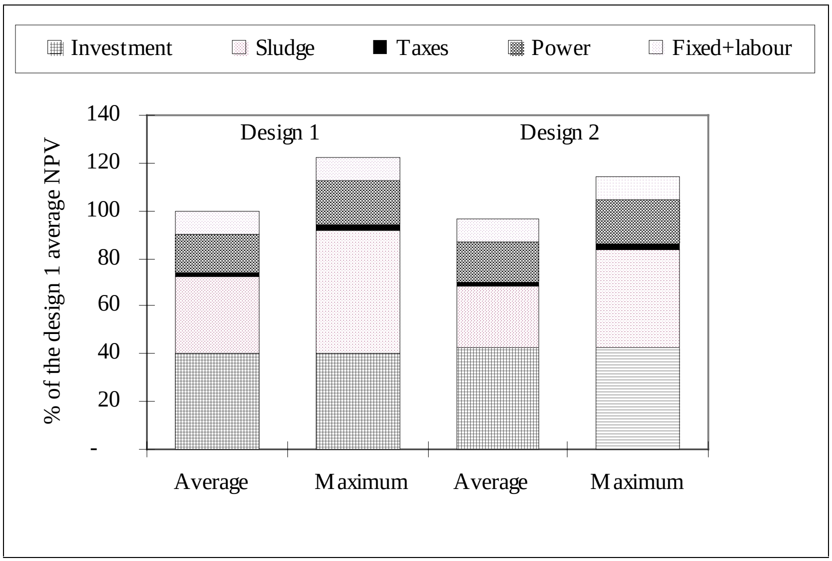
On the basis of functions, such as presented in Tables 2, 3 and 4, an overall cost index may be formulated as the NPV or the AW.

WASTEWATER TREATMENT PLANT OPTIMIZATION USING SIMULATION

Optimization of Plant Design – Steady state simulation

In the design phase of an industrial treatment plant, two sets of expected maximum loading rates (maximum conditions 1 and 2) have been considered to design an activated sludge process with biological nitrogen removal. Two reactor sizes have thus been determined and the investment cost of the larger plant has been estimated to be 5 % higher.
For both designs, the impact on the costs of the nitrogen concentration in the influent was assessed through simulation. The aim was, firstly, to assess the ability of the smallest design to treat the maximum loading rates (maximum conditions 2) to a given effluent quality and, secondly, to compare the cost of the two alternatives for average and maximum loading rates (maximum conditions 2).
Simulation results using the WEST++ simulator (Hemmis NV, Kortrijk, Belgium, http://www.hemmis.be; Vangheluwe *et al.,* 1998) showed that for both sizes investigated, the required effluent quality is reached.
The impact of the influent characteristics on the costs is illustrated in Figure 1. In this Figure, the costs are compared to the net present value of design 1 on average conditions (set to 100).

Figure 1 - Impact of the influent characteristics on the net present values

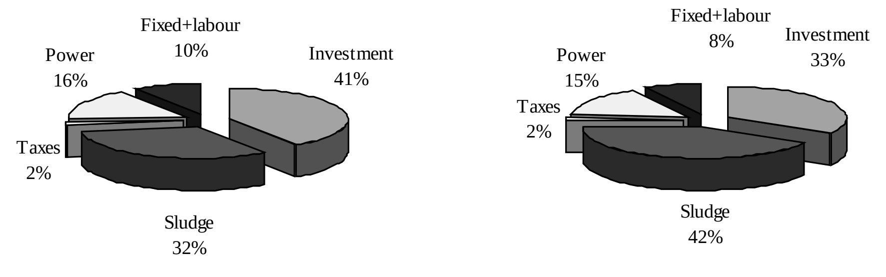


The increase in cost observed for both designs when subjected to the maximum load can mainly be attributed to an increased sludge production when the loading rates are increased. The net present value for design 2 is lower than the one for design 1, the increase in the investment cost being compensated by a decrease of the operating cost (mainly the sludge production).

Finally, it seems more economical to build a larger plant, especially if maximum loading rates are reached (NPV decreased by 7 %).

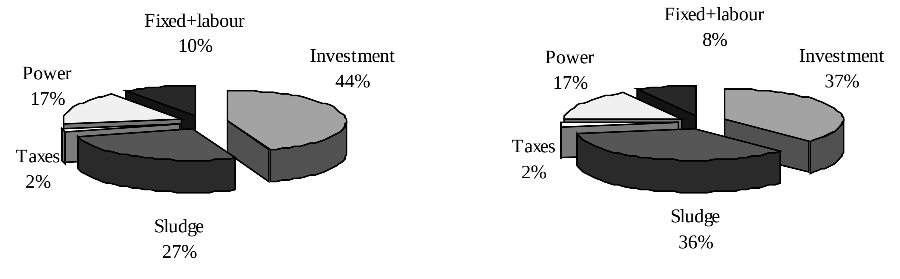
Figure 2 shows the cost breakdowns for the two designs and for the two loading conditions.

Figure 2 - Cost breakdowns



a. Design 1 - Average conditions

b. Design 1 - Maximum conditions



c. Design 2 - Average conditions

d. Design 2 - Maximum conditions

Whatever the loading rate, the cost breakdown is in agreement with literature data (Vanrolleghem *et al.,* 1996): sludge treatment and disposal represents the main operating cost, followed by the power consumption. These variable operating costs together are of the same order of magnitude as the investment cost.

This simple case study illustrates the possibility of an economic analysis coupled with simulation. The next step would consist in integrating the dynamics of the wastewater characteristics in the analysis. This would however require the assessment of the dynamic parameters of the models, uneasily determined in the design phase of a project. However, one can envisage to couple this analysis with pilot experiments, usually performed when designing an industrial WWTP. This would certainly reduce the time required to investigate different scenarios in the pilot plant, and thus would result in significant cost savings.

Optimization of Plant Operation – Dynamic simulation

To improve the effluent quality of an industrial plant (aeration tank + clarifier), in which the sludge settling properties were enhanced by continuous addition of polymer at a fixed rate, Vanderhasselt *et al.* (1999) tested several control strategies. These strategies were based on different measured variables and polymer dosing, and have been evaluated in a WWTP simulator (West++, Hemmis NV) by subjecting them to the same hydraulic and solids loading rates. To this aim, a full-scale data set of on-line effluent flow measurements and off-line sludge concentration measurements in the aeration basin were used.

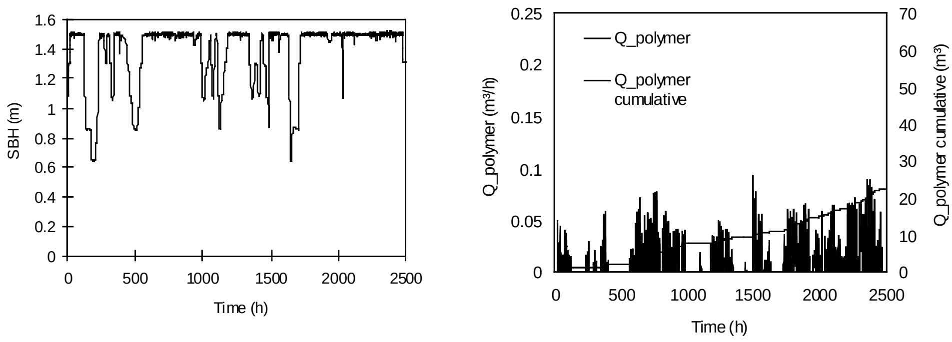
The rectangular clarifier was modeled one-dimensionally by 10 horizontal layers over which the solids fluxes were calculated. For the calculation of the settling fluxes a modified Vesilind model was used, incorporating the influence of the polymer. Experimental results led to Equation (3), obtained by regression:

$$V_s = 10.59 * e^{\frac{-X}{1.54*P+2.5}} \qquad (R^2 = 0.82) \qquad (3)$$

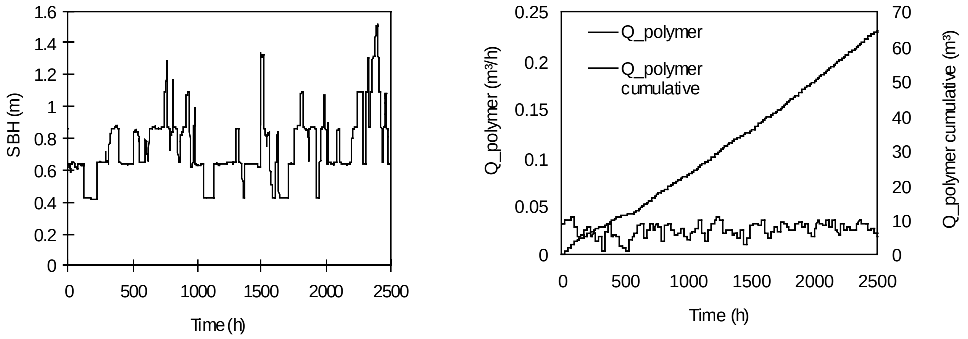
where: V_s = settling velocity (m/h)
X = biomass concentration (kg/m^3)
P = polymer concentration (ppm)

With this model, Vanderhasselt *et al.* (1999) showed that keeping the sludge blanket height (SBH) below 1.5 m leads to an effluent suspended solids concentration below 10 g/m^3. Once above this height the effluent solids concentration increases rapidly. Consequently, different control strategies were formulated to maintain the sludge blanket height below this critical level. The sludge blanket height itself, the flow rate, the solids loading and the sludge volume loading were considered as input variables to the control algorithm. Control strategies based on a combination of the SBH and one of the other measured variables were also taken into consideration. It was observed that strategies exclusively based on the flow rate require much more polymer than the other strategies to obtain the predetermined performance level (see examples in Figure 3). Still, although the other control strategies were equally effective, a clear difference could be found in their dosing pattern. Strategies using SBH show a more irregular dosing pattern while strategies that do not contain the SBH feedback component maintain a smoother behavior.

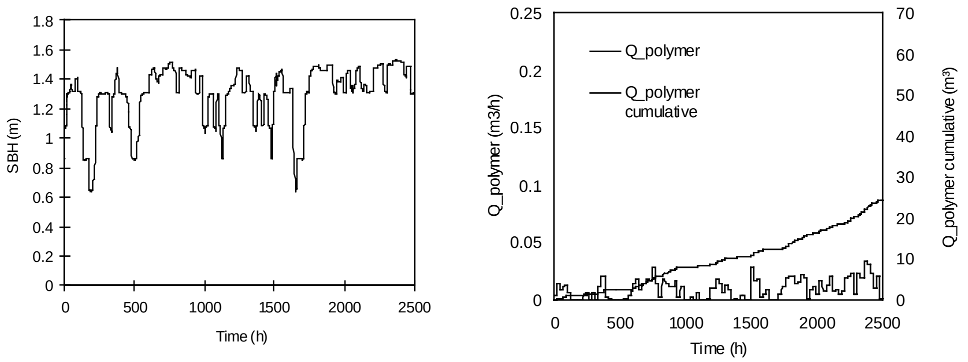
Figure 3 - Evolution of the sludge blanket height (m, left) and polymer dosing rate (m^3/h, right) as function of time for different control strategies (simulation results).



a. Control law: Q_pol = 4.1*(SBH - 1.5)



b. Control law: Q_pol = 10^{-3}*(Q_{infl} - 140)



c. Control law: Q_pol = 1.5 10^{-7}*(X_{infl}*Q_{infl} - 800000)

Practically, due to a strong density current that exists in the actual clarifier, the blanket height has to be kept below 0.5 m to achieve good effluent quality. Simulation results show that a feedback control keeping the sludge blanket height below this value allows to reduce the current polymer consumption up to 10 times compared to current constant dosing rates. Estimating the additional cost of the sensor and control system at 17000 Euro, the payback period of the control system would be less than 3 months.

CONCLUSION

When optimizing the design and operation of a plant, the definition of a standardized cost criterion is required to compare different treatment scenarios.

The integration of variable operating costs in the overall assessment of new approaches is likely to result in considerable savings, especially when real-time control strategies are investigated by dynamic modeling and simulation.

Currently, considerable efforts are devoted to directly implement the presented cost functions in a software tool, in which the design of a plant and the dynamic simulation of its behavior are evaluated simultaneously.

Further research will focus on the integration of non-monetary optimization objectives in the performance index, such as plant flexibility or the risk of failure.

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APPENDIX - POWER REQUIRED FOR A DIFFUSED AIR AERATION SYSTEM EQUIPPED WITH FINE BUBBLE DIFFUSERS AND BLOWERS

The determination of the power consumption from the oxygen transfer coefficient in field conditions (K_La_f, 1/h) consists in relating the oxygen transfer coefficient to the air flow rate, and then to the power consumption.

A1 - Determination of the delivered air flow rate

The delivered air flow rate (q_{air}) can be deduced from the oxygen transfer efficiency (OTE, -), using Equation A1, and from the constructor curves giving OTE as a function of q_{air} (Equation A2):

$$OTE = k_La_f \, Cs_{T0} \, V / \alpha q_{air} \, \rho_{O2} \, y_{O2} \qquad (A1)$$

k_La_f = oxygen transfer coefficient in field conditions (h^{-1})

Cs_{T0} = saturation concentration in clean water at T_0 ($g.m^{-3}$)
V = volume of the tank (m^3)
α = alpha factor = K_La_f / K_La
ρ_{O2} = density of oxygen ($kg.m^{-3}$)
y_{O2} = fraction of oxygen in air (-)

$$OTE = A\, q_{air}^{B} \qquad (A2)$$

Where: A, B = constant

$$q_{air} = (K_La_fCsV/A\alpha\rho_{O2}y_{O2})^{1/(B+1)} \qquad (A3)$$

A2 - Power consumption
The delivered blower power (W) can then be estimated considering an adiabatic compression (PV^{γ} = cte) (ASCE, 1992):

$$W = \gamma / (\gamma-1) * P_1 / \eta * q_{air} * [(P_2 / P_1)^{(\gamma-1) / \gamma} - 1] \qquad (A4)$$

γ = isentropic coefficient
η = efficiency of the motor and blower
P_1, P_2 = pressure before and after the compression (Pa),
$P_2 = P_1 + \Delta P + d_w / 10.33*101325$
ΔP = head losses (blower and pipes) (Pa)
d_w = water depth (m)