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Optimal Control Strategies for Wastewater Stabilization Ponds

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Abstract

In this work, we address the control problem of wastewater stabilization ponds by formulating an optimal control problem considering electrical motor power for mixers and nutrient addition rate as control variables (degrees of freedom of the problem). Nitrogen and phosphorus are the added nutrients. Constraints are embedded in the DAE model and boundaries on the control variables. As the specification on biochemical oxygen demand (BOD) in the outlet stream is far from the target one, the objective is to minimize the offset between the desired value and the current one, along a time horizon of a year. As a result of the dynamic optimization problem the optimal time profiles of motor power and nutrient addition rates (phosphorus and nitrogen) are obtained for the time horizon of a year, while the BOD is kept below the required level.

Keywords: Optimal Control, Stabilization Ponds, Wastewater Treatment.

1. Introduction

There are impacts on freshwater and coastal ecosystems associated to urban and industrial growth, and wastewater treatment processes are key to minimize their major adverse effects. Currently, activated sludge processes are the most widely used biological processes for sites where the size of land is an issue. Stabilization ponds, in turn, are large lagoons where wastewater is stored for long periods to allow a wide range of microorganisms to break down organic matter and sludge is not returned. These systems have not received great attention in literature, yet they are widely used. To highlight a few characteristics of these ponds, they present aerobic, facultative and anaerobic zones, and different chemical and biochemical processes take place within the different zones. Relationships between microalgae, heterotrophic bacteria and fungi are taken into account, which greatly influence the pond efficiency in biological wastewater treatment. We present the formulation of a detailed mechanistic model for a system of three stabilization ponds in series (two aerobic and one facultative) for control purposes within a control vector parameterization framework (PSEnterprise, 2011).

Waste stabilization ponds or lagoons offer the simplest solution for treatment of wastewater streams and are widely used in developing countries especially in rural areas. Wastewater treatment in stabilization ponds mainly results from settling and complex symbiosis of bacteria and algae where the oxidation of organic matter is accomplished by bacteria in presence of dissolved oxygen supplied by algal photosynthesis and surface re-aeration (Kargi, 2005). The major aim of wastewater treatment is to convert the waste materials into stable oxidised end products which can be safely discharged to inland or coastal waters without any adverse ecological effect. The quality of the final effluent and its volume determine the unit processes selected in the design of a wastewater treatment plant (Gray, 2004).Dynamic optimization of large size waste water treatment plants constitutes a great challenge because of the complexity of the biological process, with a heavy computational burden, and its large variations of influent in flow rate and composition. Contributions regarding dynamic optimization of wastewater treatment ponds are scarce (Luo and Biegler, 2011).

In the present work, we address the formulation of a detailed mechanistic model of a system of aerobic and facultative ponds in series, based on first principles of mass conservation. Dynamics mass balances for biomass, nutrients, dissolved oxygen and biochemical oxygen demand concentrations are formulated. The most relevant parameters of the developed model were calibrated in a previous work (Iturmendi et al. 2012) from experimental data provided by an apple and pear juice plant in Villa Regina (Argentina). It allows representing the process dynamics to be used in estimating the effluent quality under different operating conditions. Furthermore, an optimal control problem is formulated taking the engine power of the aerators' motors and nutrient dosage rate as control variables. The main objective is the minimization of the offset between the desired and real value of the biochemical oxygen demand along the time horizon of a year. Numerical results provide useful information about the complex relationships between microorganism, nutrients and organic matter concentration, as well as the optimal operation of the pond's systems.

2. Model Stabilisation Ponds

Stabilisation ponds are generally classified by the type of biological activity in anaerobic lagoon, aerobic lagoon and oxidation pond, within the latter one there are facultative pond, maturation pond, high-rate algal lagoon and Purification Lake.The main biological processes that take place in these lagoons are:

Organic matter oxidation due to respiration of aerobic bacteria.

$$C_6H_{14}O_2N + 3.35\ O_2 \rightarrow 0.12\ NH_4^+ + 0.12\ OH^- + 1.6\ CO_2 + 0.88\ C_5H_7NO_2 + 3.62\ H_2O$$

Photosynthetic oxygen production performed by algae.

$$106\ CO_2 + 16\ NH_4^+ + HPO_4^{-2} + 100\ H_2O \xrightarrow{\text{(sunlight)}} C_{106}H_{263}O_{110}N_{16}P + 103\ O_2 + 2\ H^+$$

Anaerobic digestion of organic matter.

$$CHONS + H_2O \rightarrow CH_4 + CO_2 + C_5H_7NO_2 + NH_3 + H_2S + Q$$

Factors as organic load, degree of mixing, pH, nutrients availability, solar radiation and temperature determine the biomass predomination in the different zones of the lagoons. The model takes into account dynamic mass balances of the main groups of phytoplankton: cyanobacteria (C), diatom (D) and chlorophyta (G), bacteria (B), yeast (Y), nitrate (NO_3), ammonium (NH_4), phosphate (PO_4), organic phosphorous (OP) and nitrogen (ON), dissolved oxygen (DO) and biochemical oxygen demand (BOD). This results in a complex system of differential and algebraic equations. However, homogeneous conditions are supposed in the aerobic lagoon due to the aerators, whereas two horizontal layers describe the facultative pond. Balances include inlet and outlet flows, generation, consumption, transfer between layers and volume variation terms.

$$\frac{dC_{Uj}}{dt} = \frac{Q_{IN}}{V_U} C_{IN_{Uj}} - \frac{Q_{OUT}}{V_U} C_{Uj} + r_{Uj} - \frac{k_d A}{\Delta h\, V_U}\left(C_{Uj} - C_{Lj}\right) - \frac{C_{Uj}}{h_U}\frac{dh_U}{dt} \quad (1)$$

$$\frac{dC_{Lj}}{dt} = r_{Lj} + \frac{k_d A}{\Delta h\, V_U}\left(C_{Uj} - C_{Lj}\right) \quad (2)$$

j= C, D, G, B, Y, NO_3, NH_4, PO_4, OP, ON, DO, BOD.

Where *C* represents the concentration of *j* component in the upper (*U*) an lower (*L*) layer, Q_{in} and Q_{out} represent the inlet and outlet flow respectively, r_{Uj} and r_{Lj} correspond to net generation of j in each layer, k_d is the diffusion rate between layers, *h* is the water column height, *A* is the pond transversal area, *V* is the pond volume, Δh is the sum of the middle height of each layer. An overall mass balance is also formulated, where contributions of rain (Q_{rain}) and evaporation (Q_{evap}) are considered.

$$\frac{dh_T}{dt} = \frac{1}{A}\left(Q_{in} - Q_{out} + Q_{rain} - Q_{evap}\right) \quad (3)$$

Where h_T is the total water column height. The external forcing functions for the model were temperature, solar radiation, precipitation, evaporation, inlet flow, inlet concentration of nitrogen and phosphorous. Sinusoidal functions were used to approximate them. Other algebraic equations correspond to generation and consumption of modelled biomass. They consider production and loss due to basal metabolism (respiration, excretion and natural mortality), settling and grazing (Estrada, 2008).

$$r_{ij} = R_{ij,growth} - R_{ij,met} - R_{ij,sett} - R_{ij,graz} \quad (4)$$

j= C, D, G, B, Y.
i= Upper layer, Lower layer.

Nutrients availability, temperature, pH and light intensity impact on biomass growth and are included thought limiting functions using a multiplicative model. This type of functions decrease the maximum growth rate by taking values between 0 and 1.

$$R_{ij,growth} = k_{ij,growth} f(T)_{ij} f(N)_{ij} f(pH)_{ij} f(I)_{ik} f(BOD)_{il} \quad (5)$$

j= C, D, G, B, Y. *k*= C, D, G.*l*= B.
i= Upper layer, Lower layer.

Physical, chemical and biochemical reactions are highly influenced by temperature. In general, organic matter degradation rate increases with temperature. On the other hand, light intensity plays a fundamental role in the photosynthetic activity. Steele's equation with Beer's law is used to model its effect though the water column depth.

Nutrient limitation is modelled in different ways depending on the type of biomass. Monod type kinetics is used to model internal phosphorous concentration as limiting nutrient for algae groups and to model ammonium concentration as limiting nutrient for yeast. In the case of bacterial growth, nutrient limitation is calculated using a Monod type kinetic and Liebig's "Law of the minimum" that the extent of growth is determined by the nutrient in least supply. Biochemical oxygen demand limits bacterial growth. It is also assumed to be a Monod type.

In addition, the pH in stabilization ponds tends to rise depending on the rate of phytoplankton's photosynthetic activity and utilization of bicarbonate ions. Its dependency of biomass growth is assumed to be a Monod type, except for yeast growth where an experimental equation is used. Biomass basal metabolism includes all internal processes that decrease biomass concentration. It is assumed to increase exponentially with temperature, following an Arrhenius' type behaviour.

3. Control Strategies

The main objective of a wastewater treatment plant is to keep the BOD concentration in the effluent at an acceptable level. This must be achieved without releasing an excessive amount of nutrients in the receptor body.

Wastewater treatment at insufficient nutrient levels often results in poor quality effluent. Generally, carbon adsorption rate is greater than other nutrients uptake rate leading to phosphorous and nitrogen deficiency in the biomass. This imbalance can only be overcome by increasing the concentration of these deficient nutrients. So, to operate the biological process, phosphorous and nitrogen must be added to the nutrient deficient wastewater (Lindblom, 2003). Nitrogen is added in the form of urea ($(NH_2)_2CO$). Urea dissolves slowly when diluted in water and ends up as ammonium and CO_2. Phosphorous is added in the form of NP granules. This salt consists of NH_4-N (14%), NO_3-N (12%) and PO_4-P (6%). Furthermore, the supply of oxygen provided by mechanical aerators is taken into account to ensure the necessary amount of oxygen. Oxygen transfer rate is assumed to be proportional to power engine of aerator's motors and inversely proportional to stabilization pond volume.

4. Dynamic Optimisation: Optimal Control

We consider processes described by mixed differential and algebraic equations of the form:

$$f((x(t), \dot{x}(t), y(t), u(t), v) = 0 \tag{6}$$

Here *x(t)* and *y(t)* are the differential and algebraic variables in the model while $\dot{x}(t)$are the time derivatives of the*x(t)* (i.e.,$\dot{x}(t) = dx/dt$). *u(t)* are the control variables and *v* the time invariant parameters to be determined by the optimisation (PSEnterprise, 2011).Dynamic optimisation seeks to determine the values of the time invariant parameters, *v*, and the time variation of the control variables, *u(t),* over the entire time horizon so as to minimise the final value of a single variable z.

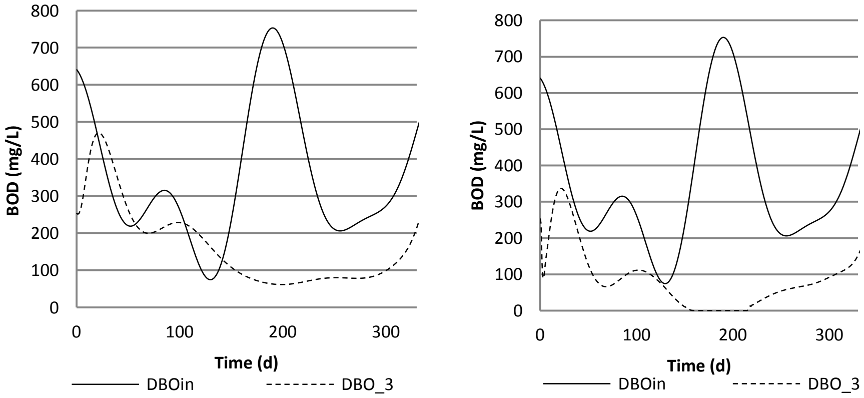
$$z = \int_0^{t_f} (C_{BOD} - C_{BOD\ setpoint})^2\, dt \tag{7}$$

We have formulated a dynamic optimisation problem in an equation oriented control vector parameterization environment. In this approach, control variables (degrees of freedom that are time dependent, if any) are approximated by piecewise-constant, piecewise linear or, in general, polynomial functions, over a specified number of control intervals, and optimization parameters (time independent degrees of freedom, like parameters in a parameter estimation problem) are also approximated. Therefore, an NLP is formulated at the outer level, with coefficients of these polynomials (if any) and parameters as optimization variables. In the inner level, with fixed values for parameters, there are no degrees of freedom and the differential algebraic equations

(DAE) system can be integrated with a BDF (Backward Differentiation Formulae) strategy, with sparse matrix techniques in the DASOLV routine. At this step, also the partial derivatives of differential and algebraic equations with respect to the optimization variables (parameters to be estimated) have to be determined along the integration horizon. They are obtained by integrating the sensitivity equations, along with the original DAE system. Information on objective function, constraints and sensitivities (the gradients of the constraints and the objective function with respect to parameters to be estimated at each instant of time) is transferred to the external NLP problem, in which parameter values are updated in the NLP and new values for parameters are proposed to proceed with the inner DAE system solution.

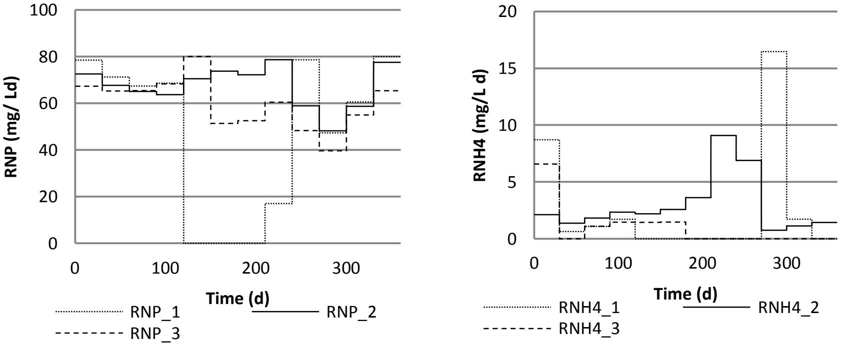
5. Numerical Results

In this section, results of the optimal control are presented. Our main objective is to minimise BOD concentration in the effluent. In Figure 1(a) are shown the inlet and outlet BOD concentration of the system of 3 lagoons, whereas in Figure 1(b) the same variables are presented after implementing the control strategies.



(a) No control (b) With control

Figure1. Biochemical Oxygen Demand concentration: inlet stream (in), outlet stream the facultative pond (3).



(a) (b)

Figure 2. (a) NP dosage rate profiles. (b) Ammonium dosage rateprofiles.

The optimal dosage rate profiles are shown in Fig 2 for the three lagoons. Aerator motor power's profiles are not shown but results indicate that they must operate at maximum power.

Peak on inlet BDO at approximately t=200 is due to the higher amount of organic contents of the plant effluent at such time, which corresponds to summertime. Strategies are being developed to increment the size of the treatment facility in order to keep this value at a lower level.

6. Conclusions

We presented the formulation of a detailed mathematical mechanistic model for a system of stabilization ponds for control purposes within a control vector parameterization framework, obtaining optimal profiles for the control variables: motor power and nutrient addition rates. The model parameters are found for a system of stabilization ponds within an industrial facility of juice production. The amount of organic waste in the effluents of the plant requires an optimal control strategy for nutrient addition and mixing in the aerobic lagoons.

Numerical results provide useful information on the complex relationship among microorganisms, nutrients and organic matter concentration, as well as optimal management of the system of ponds. Another aerobic lagoon could allow for lowering this value. It is worth pointing out that the outlet BDO from the system is always lower than the inlet BDO after implementing the control strategies, as expected. It is suggested that agitators operate at maximum power all the time, while optimal profiles of nutrient inlet flow rates that minimize the DBO have been found for a time horizon of one year.

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