



Modeling and optimization of activated sludge bioreactors for wastewater treatment taking into account spatial inhomogeneities



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ABSTRACT

In this work, we study optimal and suboptimal control strategies for the treatment of a polluted water resource by using aside a continuous bioreactor. The control consists in choosing the inlet volumetric flow rate for filling the bioreactor with contaminated water from a considered resource (lake, reservoir, water-table, ...). The treated outflow returns to the resource. We tackle an optimization problem which aims to minimize the time needed to reach a prescribed minimal value of contamination in the resource by choosing the input flow. Next, we study the influence of inhomogeneities of concentrations in the bioreactor, considering a system based on partial differential equations which describe its dynamics. We show that applying the optimal feedback control derived for perfectly mixed bioreactor does not allow to reach the target with small diffusion parameters as it drives the bioreactor to washout (the bioreactor equilibrium with no biomass). In this case, a suboptimal feedback (which reaches the target in finite time) is obtained with the help of a Hybrid Genetic Algorithm. Furthermore, we consider that the fluid flow velocity of the water entering into the bioreactor follows either a uniform or a nonuniform profile, showing that the optimal volumetric flow rates obtained with the uniform profile are not optimal if the profile is nonuniform, even when high diffusion coefficients are considered in the model.

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1. Introduction

The decontamination of water resources is a major environmental issue in the areas of prevention of eutrophication and wastewater treatment. Eutrophication is a process whereby water resources becomes too rich in organic material and mineral nutrients. Household products (phosphorus detergents) and products used in agriculture (nitrate fertilizers) are the main causes of pollution of water resources. As a result, some plants (in particular planktonic algae) can grow rapidly and reduce the available oxygen of the aquatic ecosystem resulting, for instance, in the death of local bio-organisms (such as fishes). The *activated sludge process* is a way of eliminating eutrophication from water resources. The process uses biomass (i.e., bacteria) to feed with substrate (i.e., the organic contaminant) in wastewater, producing a high quality effluent for

a reasonable operating and maintenance cost. It consists of several interrelated components:

- A tank where the biological reaction occurs, called bioreactor. Bacteria thrive as they travel through the bioreactor and they multiply rapidly with sufficient food (substrate).
- A waste water source that feeds the bioreactor.
- A settler situated at the bottom of the bioreactor, separating bacteria from the clearer water. This accumulated bacteria is called *activated sludge*.
- A means of collecting the activated sludge, either to return it to the bioreactor or to remove it from the process.

The optimization of activated sludge processes has received a great attention in the literature (see, e.g., [1–3] for reviews of the different optimization techniques that have been used in bioprocesses). The objective is usually to control the inlet flow rate of the bioreactor for attaining a prescribed target (e.g., a small prescribed amount of pollutant at the bioreactor outlet) in a finite given time. Particularly, the maximization of bacteria production in a well

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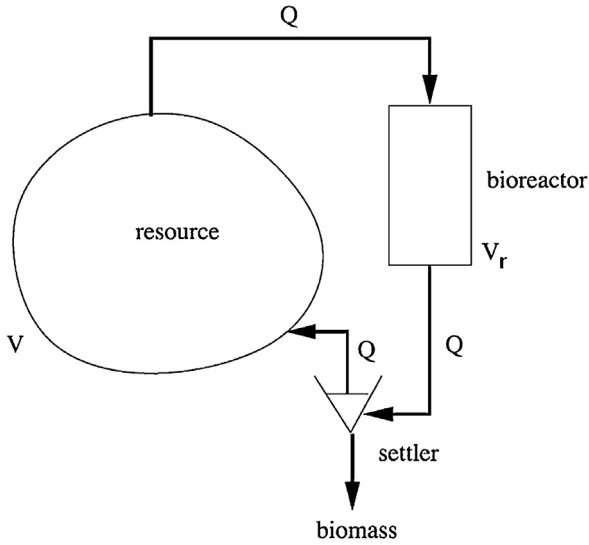


Fig. 1. Connection of the bioreactor with the resource.

mixed fed-batch bioreactor has been studied using different optimization techniques, as Pontryagin Maximum Principle (see [4]), Genetic Algorithms (see [5–8]) or Hybrid Stochastic-Deterministic Methods (see [4,9]). The effects of varying the inlet flow velocity and the substrate concentration input in bioreactors have been studied as well (see for instance [10–13]). The biological purification of waste water is an example of application of bioreactors (see [14–16]).

In this work, we consider a natural resource polluted with a substrate concentration S_r . The objective of the treatment is to decrease S_r , as fast as possible, to a target value S_{lim} , by using a bioreactor. The bioreactor is fed from the resource with a volumetric flow rate Q , and its output returns to the resource with the same flow rate Q . Typically, introducing biomass in the resource is avoided because of the risk of having bacteria growing in competition with other populations that also need oxygen. Therefore, we assume that the resource contains only undesirable chemical substrate, that we assume to be uniformly spatially distributed all the time. To do so, the bacteria present in the bioreactor are filtered by a settler at the output so that they do not enter the resource (see Fig. 1).

This problem was tackled in [15] under the assumption of having a well-mixed environment, i.e., the concentration of substances were assumed homogeneous both in the water resource and in the bioreactor. Nevertheless, the activity of the bacteria inside the bioreactor induces a gradient of substrate concentration, which can be negligible or not, depending notably on the ratio between the advection and diffusion effects of the physical system. We aim at studying the influence of this gradient on the optimal inlet volumetric flow rate. Following [15], we characterize the optimal policies among constant, time-dependent and feedback controls and study the possible benefits of using non-constant flow rates. Additionally, our optimization results are compared with those obtained in [15].

The paper is organized as follows: Section 2 introduces an ODE model describing the behavior of the contamination in the water resource and two models describing the dynamics of the bioreactor, using ODEs and PDEs, respectively. In Section 3, we state the optimization problem, which aims to minimize the time needed to decontaminate the water resource. We also present the optimization methods used in both ODE and PDE models. In Section 4 we explain the numerical experiments carried out for the optimization problem and shows the results. Section 5 draws the conclusions after the comparison between the numerical results obtained with the ODE and PDE models.

2. Mathematical modeling

Here we detail the mathematical models used to describe the dynamics of the bioreactor and the water resource. More precisely, in Section 2.1 we present an ODE system under the assumption of uniform concentration of contaminant in the resource. We justify such an assumption for very large resource volumes for which the treatment takes long time. The output flow Q induces then a very small dilution rate of the contaminant in the resource compared to the diffusion of the contaminant, that maintains an (almost perfectly) homogeneous distribution in the resource. As the bioreactor volume is much smaller, the induced advection could make the assumption of homogeneous concentrations inside the bioreactor questionable depending on the process characteristics (reactor shape, agitation, diffusivity, ...). Then, in Section 2.2 we introduce two different models which describe the behavior of the concentrations inside bioreactor.

2.1. Water resource model

Since we assume homogeneous distribution of substrate in the water resource, its dynamics can be described as follows [15]:

$$\begin{cases} \frac{dS_r}{dt} = \frac{Q}{V}(S_{out} - S_r) & t > 0, \\ S_r(0) = S_{r,0}, \end{cases} \quad (1)$$

where S_r (mol/m³) is the concentration of substrate in the water resource; V (m³) is the water resource volume; Q (m³/s) is the volumetric flow rate and S_{out} (mol/m³) denotes the concentration of substrate concentration at the outlet of the bioreactor, which is calculated differently depending on the mathematical modeling considered for the bioreactor.

The explicit solution of (1) is

$$S_r(t) = e^{-\int_0^t \frac{Q(s)}{V} ds} \left(\int_0^t \frac{Q(s)}{V} S_{out}(s) e^{\int_0^s \frac{Q(\tau)}{V} d\tau} ds + S_{r,0} \right). \quad (2)$$

2.2. Bioreactor models

Section 2.2.1 presents an ODE system under the assumption of uniform concentration of substances in the bioreactor and Section 2.2.2 introduces a PDE system in order to study the influence of inhomogeneities in the tank. In both sections, $\mu(\cdot)$ (s⁻¹) denotes the growth rate function, which refers to the growth rate of the biomass in function of the substrate concentration. We assume that

$$\mu(\cdot) \text{ is increasing and concave with } \mu(0) = 0. \quad (3)$$

An example of such a growth rate function is given by the Monod equation (see, e.g., [15,17,18]), which is used to relate microbial growth rates in an aqueous environment to the concentration of a limiting nutrient. Its general expression is:

$$\mu(S) = \mu_{\max} \frac{S}{K + S}, \quad (4)$$

where μ is the specific growth rate of the microorganisms, S is the concentration of limiting nutrient for growth, $\mu_{\max}$ is the maximum specific growth rate of the microorganisms and K is the half-maximum kinetics constant, i.e., the value of S for which $\mu(S) = \frac{\mu_{\max}}{2}$. We observe that $\mu_{\max}$ and K are empirical coefficients, that differ between species and are based on the ambient environmental conditions.

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