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Comparison of control strategies for nitrogen removal in an activated sludge process in terms of operating costs: A simulation study

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ABSTRACT

In this paper several control strategies for nitrogen removal are proposed and evaluated in a benchmark simulation model of an activated sludge process. The goal is to determine which control strategy delivers better performance with respect to plant operating costs. In the study, constant manipulated variables and various PI and feedforward control strategies are tested and compared with predictive control, which uses an ideal process model. The control strategies differ in the information used about the process (number of sensors and sensor location) and in the complexity of the control algorithms. To determine the set-points that yield optimal operating costs, an operational map is constructed for each control strategy. Results of the simulation show that with PI and feedforward controllers almost the same optimal operating costs can be achieved as with more advanced MPC algorithms under various plant operating conditions. More advanced control algorithms are advantageous only in cases where the plant is highly loaded and if stringent effluent fines are imposed by legislation.

1. Introduction

Water pollution represents one of the most serious environmental problems due to the discharge of nutrients into receiving waters. Hence, stricter standards for the operation of wastewater treatment plants (WWTPs) have been imposed by authorities. In order to meet these standards, improved control of WWTPs is needed. WWTPs should be controlled in such a way that plant operating costs (OC) are minimized, while effluent standards are still maintained.

Different control algorithms for WWTPs have been introduced over the years. For instance, sufficient nitrification can be maintained by applying a constant aeration flow rate, by control of the dissolved oxygen (DO) level at a pre-selected set-point or by using a variable DO set-point controller based on ammonia concentration in the last aerated reactor of the plant (Ingildsen, 2002; Vrečko et al., 2003). On the other hand, the denitrification process is usually controlled by manipulating the external carbon flow rate or internal recirculation flow rate based on nitrate concentration in the last anoxic reactor or in the last aerobic reactor (Lindberg, 1997; Yuan et al., 2002). In recent years different control algorithms have been proposed, from simple ON/OFF and PI control (Ayesa et al., 2006) to complex model predictive control (MPC) (Steffens and Lant, 1999). Unfortunately, various plant configurations, influent characteristics and evaluation criteria have been used in the assessment of control algorithms. As all of these factors influence the choice of a control strategy, it is difficult to say which control algorithm is the most appropriate with respect to minimal OC and best effluent quality, and whether the implementation of complex control algorithms is really necessary.

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This paper presents several control strategies for nitrogen removal that were designed and tested on a benchmark simulation model of an activated sludge process (ASP). Control strategies differ in the information used about the process (i.e. the number of sensors and sensor location) and in the complexity of the control algorithms. Constant manipulated variables and PI and feedforward (FF) controllers were tested, as well as an advanced MPC controller, which was used as a reference for the other control strategies. In this way the control strategy that produces optimal performance regarding OC and yields satisfactory removal of nutrients can be found.

The paper is organized as follows: In the following section a benchmark simulation model is presented. Then the applied control strategies are described, followed by set-point analysis. Next, the presented control strategies are assessed and compared in terms of OC at various plant operating conditions. Finally, the most important conclusions are drawn.

2. Materials and methods

2.1. *Benchmark simulation model*

A benchmark simulation model of an ASP was developed by working group No. 1. within COST Actions 624 and 682. The benchmark is a simulation protocol defining a plant layout, a process model, influent data, test procedures and evaluation criteria (Copp, 2002).

2.1.1. *Plant layout and process model*

The benchmark represents a pre-denitrification plant with two anoxic and three aerated compartments (Copp, 2002). However, in our case one anoxic and four aerobic reactors were used (Fig. 1) in order to achieve lower effluent ammonia concentrations. The IWA activated sludge model No. 1 (ASM1) is used to describe the biological processes in the reactors. A further description of ASM1 can be found in Henze et al. (2000). The secondary settler is modelled as a non-reactive, 10-layer process with a double exponential settling velocity model proposed by Takács et al. (1991).

2.1.2. *Influent data and test procedures*

The benchmark influent data include three influent files for three different weather conditions: dry, rain and storm. Each of these files contains 14 days of data at 15-min intervals. To calculate benchmark performance the plant is first run to steady state by simulating the plant with the defined constant influent file over a 150-day period. Then, the plant simulation continues by first applying 14 days of the dry influent weather file, followed by 14 days of dry, rain or storm influent file. The performance of the benchmark is then evaluated for the last 7 days of dynamic data.

2.1.3. *Evaluation criteria*

Various criteria have been defined in the benchmark (Copp, 2002) to assess the performance of the plant. In this work, OC that combine aeration costs, sludge disposal costs, external carbon dosage costs and effluent fines were used to evaluate control strategies, without taking into account the investment costs for the implementation of the control strategy (sensors, actuators). Within the benchmark, pumping costs are also defined, but were not considered in our case, as all the pumping flow rates were kept constant. The operating costs [€/d] were calculated as follows:

$$OC = \gamma_1 AE + \gamma_2 SP + \gamma_3 EC + EF, \tag{1}$$

where AE is aeration energy, SP is sludge production for disposal, EC is external carbon addition, while EF means effluent fines. The weights γ_1, γ_2 and γ_3 were set in proportion to the weights in the operating cost index (OCI) in the benchmark. The OCI weights (γ_1, γ_2 and γ_3) were defined by the benchmark group and were set according to the relative contribution of AE, SP and EC to operating costs. Based on the experience gained from the WWTPs operation they were chosen to be 1, 5 and 3, respectively. In our case, a rough estimate of average electricity price in EU (0.1 €/kWh) was also taken into account and thus all the weights were multiplied by 0.1. Hence, the final values for γ_1, γ_2 and γ_3 were 0.1 €/kWh, 0.5 €/kg and 0.3 €/kg, respectively.

Average aeration energy (AE [kWh/d]) is calculated for the last 7 days of dynamic data (*T*). The equation suggested in Copp (2002) was improved by also including the volumes of the aerated reactors (Jeppsson, 2005):

$$AE = \frac{24}{T}\int_{t=7d}^{t=14d}\sum_{i=2}^{5}\left[0.0007\times K_L a_i(t)^2\left(\frac{V_i}{V_{ref}}\right) + 0.3267\times K_L a_i(t)\left(\frac{V_i}{V_{ref}}\right)\right]dt, \tag{2}$$

where $K_L a_i$ is the oxygen transfer rate (d^{-1}) in the individual aerated reactor, V_i is the volume of the ith reactor and V_{ref} is 1333 m^3.

Sludge production (SP) for disposal (kg/d) is calculated based on the amount of total suspended solids in the wastage

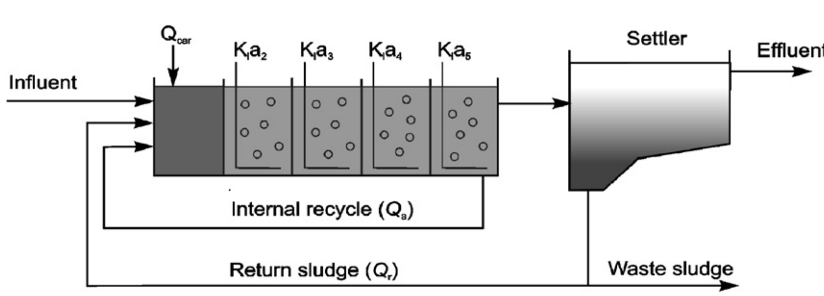

Fig. 1 – Plant layout.