REDUCTION OF AN ACTIVATED SLUDGE PROCESS MODEL TO FACILITATE CONTROLLER TUNING

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KEYWORDS

Activated sludge process, modelling, model reduction, controller tuning

SUMMARY

The aim of this paper is to present a reduced model of an industrial activated sludge process which can be used for controller tuning. A reduced model was required because use of the full model is time consuming and computer intensive. The resulting model decreased simulation time by a factor of 3. Evaluation of the reduced model showed that it gives a good approximation of the full model, however, at intermediate influent concentrations of free ortho-phosphate the performance is lower. This did not significantly affect the controller tuning. Therefore, this simple model reduction is an effective tool for tuning the controller.

INTRODUCTION

The process under study is part of an industrial wastewater treatment plant (WWTP) with an average influent flow of 2700 m^3/d. A characteristic of this WWTP is that the influent concentration of COD (Chemical Oxygen Demand) is extremely high (in the range of 1000 to 4000 g COD/m^3, with peaks up to 9000 g COD/m^3) and can vary dramatically over time because of the batch-wise production of different products in the industrial plant.

This study is confined to the activated sludge process with recycle as depicted in figure 1. The wastewater containing substrates and some biomass comes from the previous unit in the treatment plant and enters the activated sludge units (ASUs). In these units the substrates are converted aerobically by the biomass to more biomass, inert substances and CO_2. The stream then continues to the clarifier, which separates the biomass from the effluent using gravity. Most solids are returned to the activated sludge units. Some of the settled biomass is wasted to maintain a solids residence time of 30 h on average.

The wastewater contains a very high load of COD but is deficient in terms of phosphorus, that is, a lack of phosphorus is limiting the growth of the biomass. Phosphorus must be added to the system to increase the performance of the activated sludge units in terms of degradation of the COD in the wastewater and maintaining a stable biomass. A controller has been designed for the addition of the phosphorus (in the form of ortho-phosphate) using a model of the process.

Modelling of such a system is not new and a variety of models exist for both the reactions occurring in the activated sludge units (Henze *et al.*, 1987) and the settling (Takàcs *et al.*, 1991; Otterpohl and Freund, 1992). These models are characterized by their complexity and highly non-linear nature. When these models are used for control purposes problems arise with respect to the time needed for tuning the controllers, since the optimized settings for the controller are found by performing

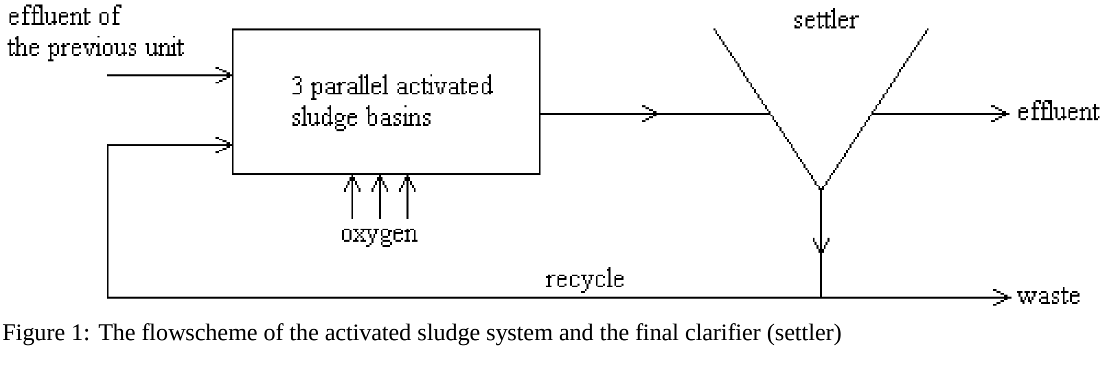

Figure 1: The flowscheme of the activated sludge system and the final clarifier (settler)

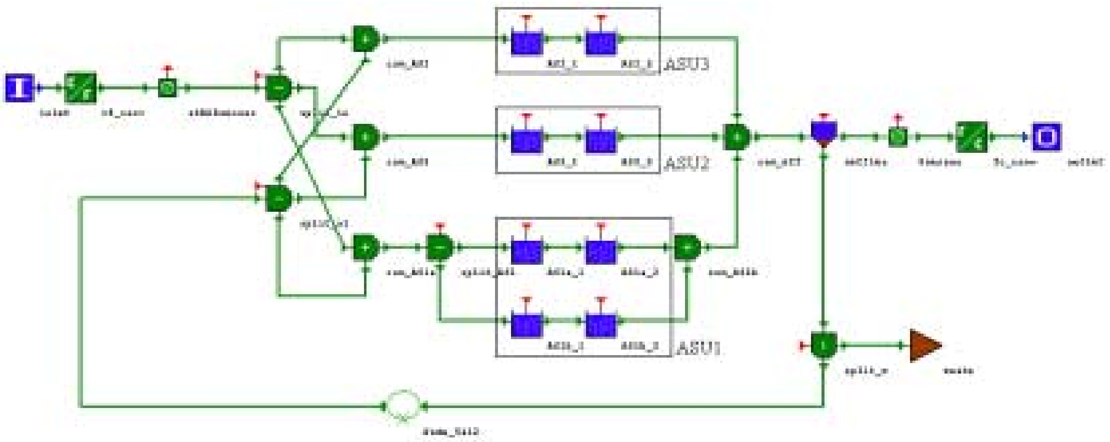

Figure 2: The unreduced model of the activated sludge process

multiple simulations. In the following section, first, a complete, unreduced model will be presented and, then, a solution to this problem, that is, a reduced model, will be presented. The reduced model is analyzed to determine its limitations and the effect of these limitations on controller tuning are discussed.

THE UNREDUCED MODEL

The unreduced model of the process combines models of the hydraulics of the system, biological reactions in the activated sludge units and the separation process in the settler. The model was simulated with WEST. WEST is a distributed, multi-platform modelling and simulation environment designed for WWTPs. The units in the WWTP are represented by mass balances in the form of differential and algebraic equations which were solved using the Runge-Kutta 4-method with variable stepsize.*

The hydraulic modelling

The system consists of 3 parallel lanes flowing to the settler and one recycle flow. A tracer study was performed to determine the system hydraulics (Coen *et al.*, 1998). Two of the lanes (ASU2 and ASU3) behave as two CSTRs (Continuous Stirred Tank Reactors) in series and the third (ASU1) as two lanes of two CSTRs in parallel.

The recycle flow and the influent wastewater are not equally distributed over the three lanes. Table 1 lists the split fractions of the flows over the lanes. The wastewater is split up over the three units unevenly, while the recycle is split up evenly over the three lanes. This means that the units are unequally loaded: ASU2 has a significantly lower load than ASU1 and ASU3.

Table 1: Fractions of the wastewater flow and the return sludge flow divided over the activated sludge units

	ASU1	ASU2	ASU3
wastewater	0.36	0.24	0.40
recycle sludge	0.35	0.31	0.34

Modelling of the reactions

The model describes carbon removal and accounts for the phosphorus deficiency in the system. It is a modified version of the IAWQ Model No.1 (Henze *et al.*, 1987). This model is a complex, highly non-linear model due to the Monod-type expressions that it uses. It has 35 parameters and 15 states per tank. Most parameters are set at the default values (Henze *et al.*, 1987) except for the yield of biomass growing on substrate ($Y_H = 0.67$), the maximum specific growth rate of the biomass ($\mu_{max} = 0.408$) and the decay rate of the biomass ($b_H = 0.312$), which were determined using the methods given in Vanrolleghem *et al.* (1999).

Settler modelling

The final clarifier was modelled as a point settler, that is, as a separator with the split fraction of water determined by the recycle rate, which is 3000 m^3/d and the solids split fraction (the fraction of settler influent solids that goes to the effluent) assumed to be 0.03. It is not a dynamic model.

Model input

As input for the model, files were constructed from data measured on-site combined with information retrieved from lab-scale experiments.

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[*] For more information on WEST see http://www.hemmis.be

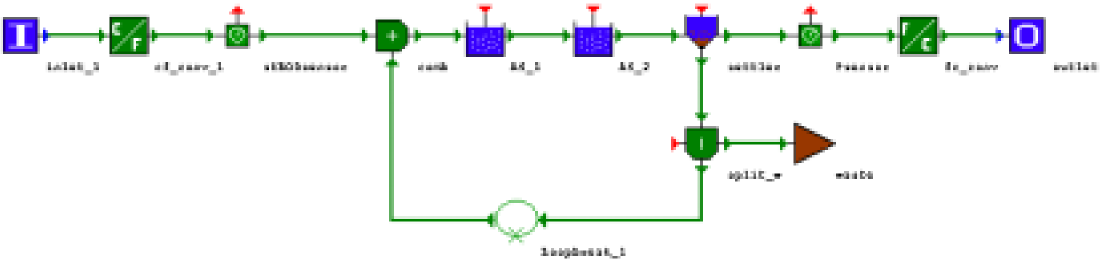


Figure 3: Reduced model of the activated sludge process

The controller

A PI-controller was designed to dose phosphorus (75 %(m/m) phosphoric acid) to the system. The measured variable is the effluent concentration of phosphate and the manipulated variable is the flow of the phosphoric acid solution to the system. The aim of the controller is to maintain the effluent concentration of phosphate at a setpoint Y_S below a level which satisfies goverment restrictions. This ensures that sufficient phosphorus necessary for a healthy biomass is present in the system without endangering effluent quality.

Summary

The resulting model has 120 states. Simulation time of the unreduced model is 3.5 minutes for a dynamic simulation of 3 months. When the controller is implemented, this simulation time increases to 13.5 minutes due to the increased stiffness. A reduced model which is more time efficient will be described next.

THE REDUCED MODEL

In order to decrease the calculation time, the model was reduced to a 2-tank configuration as can be seen in figure 3. The approximation was made that the wastewater and the recycle are evenly distributed over the 3 lanes, that is, that the three lanes behave in a similar way.

For each of the activated sludge units the initial values of the derived state variables were summated as follows: all the initial values of the derived state variables in the first tanks in the three lanes were summated. The same was done with the second tanks in each of the lanes. The result of this method is that the total volume of the resulting two tanks in the reduced model is the same as the summation of the separate tanks in the unreduced model. The concentrations of the different species are the (weighted) average of the concentrations in the tanks of the unreduced model.

The reduced model has 30 states. A dynamic simulation of 3 months now takes 1 minute to complete. When the controller is implemented, this takes 4.3 minutes. So the simulation time

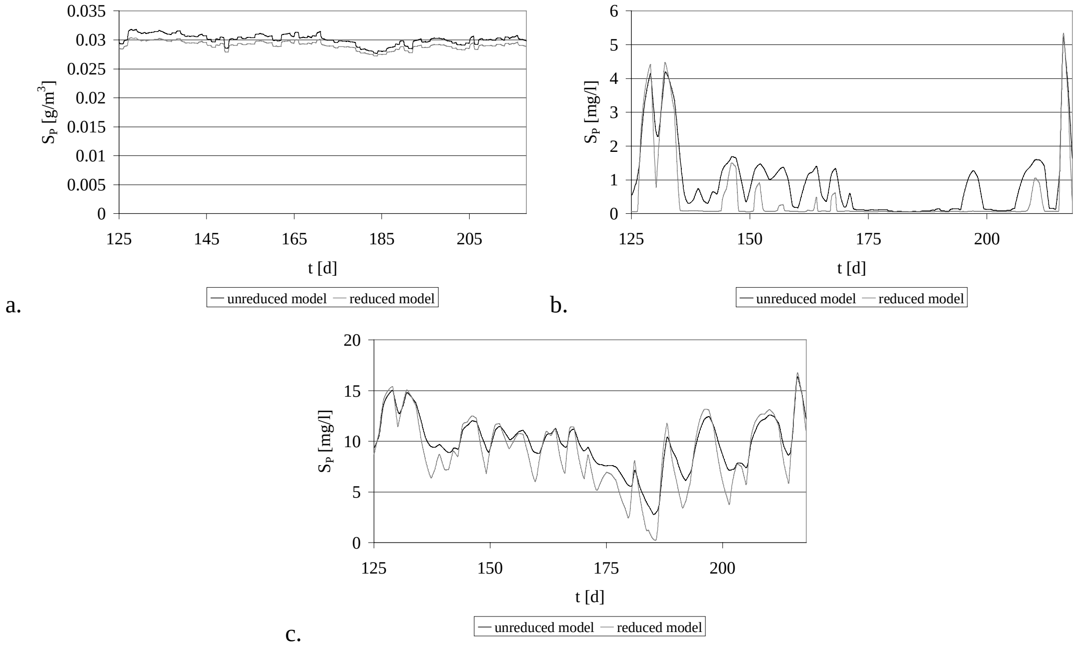


Figure 4: Effluent concentrations of S_P calculated with the unreduced and the reduced model: a. $S_{P,in}$ = 1 mg/l; b. S = 10 mg/l; c. S = 20 mg/l

has reduced three-fold. The question now is, how good is the approximation? That is, does the reduced model still adequately describe the process? This will be discussed next.

EVALUATION OF THE MODEL REDUCTION

The effect of the influent on the quality of the model reduction was evaluated using different constant influent concentrations for free ortho-phosphate (S_P). This is illustrated in figure 4 for three different influent concentrations of S_P ($S_{P,in}$).

There is an important observation with regard to the dynamic behaviour of the unreduced and the reduced models. The reduced model amplifies the dynamic behaviour of the system, that is, it has a greater standard deviation. There are two notable differences in the effluent concentration:

- the difference in the range of the simulated effluent concentration; and
- the sensitivity of the simulated effluent concentration to the type of model.

The range of the simulated effluent concentration changes with different values for $S_{P,in}$. If there is excess S_P in the influent, the S_P that has not been used will be present in the effluent. It is clear that the performance of the reduced model when compared with the unreduced model is dependent on the concentration of S_P in the influent. This sensitivity to model reduction is plotted for different influent concentrations in figure 5, where the sensitivity is defined as:

$$\mathbf{S}_{S_P} = \left| \frac{\overline{S}_{P,unreduced} - \overline{S}_{P,reduced}}{\overline{S}_{P,unreduced}} \right|_{t_{start} \le t \le t_{end}} \qquad (1)$$

The variation in sensitivity to model reduction for changing $S_{P,in}$ is related to the behaviour of the system under two different conditions: P-limiting with low biomass growth and P-sufficient with high biomass growth.

This results in:

1. At low concentrations all of the tanks in the reduced and unreduced model are phosphorus limited. This results in a low sensitivity;
2. At high concentrations none of the tanks in the two models are phosphorus limited (see figure 6a.). This also results in a low sensitivity; and
3. At intermediate concentrations some of the tanks are phosphorus limited and some are not. This results in a large value of the sensitivity.

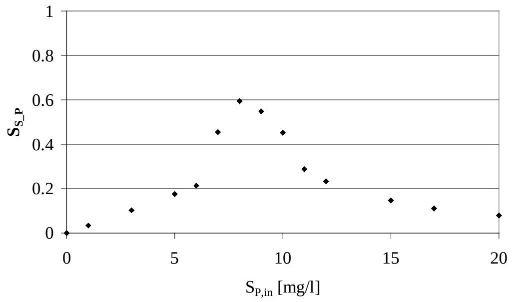


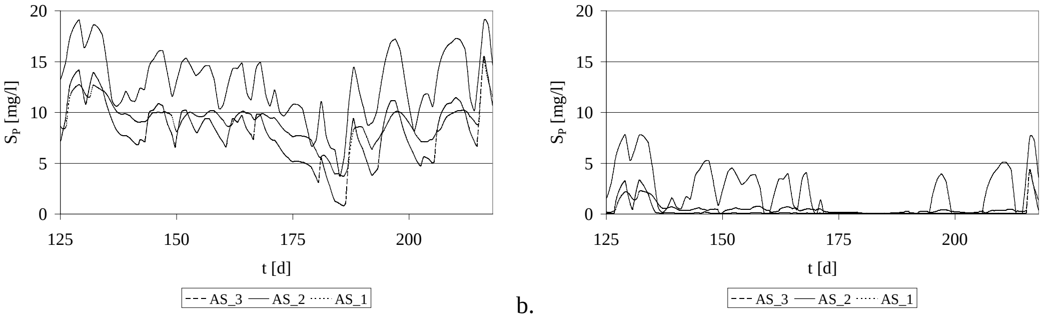
Figure 5: Sensitivity to model reduction of the concentration of S_P in the influent as a function of $S_{P,in}$

At intermediate concentrations the reduced model is phosphorus limited below 8 mg/l. However, in the unreduced model, due to an uneven distribution of wastewater across the three lanes (see Table 1), some tanks are in phosphorus limited conditions and some are not. This means that the reduced model is no longer a good approximation of the unreduced model. Figure 6a. illustrates this. Obviously, their average is different from the dynamics predicted by the reduced model which is not in phosphorus limiting conditions

In conclusion, the reduced model is not a good approximation of phosphorus dynamics at intermediate $S_{P,in}$. We now consider how this affects the controller.

EFFECT OF MODEL REDUCTION ON CONTROLLER TUNING

The effect of the model reduction on controller tuning was examined both in the region of high sensitivity (intermediate $S_{P,in}$) and low



a.

b.

Figure 6: Effluent concentrations of S_P from the three units for: a. $S_{P,in}$ = 20 mg/l; and b. $S_{P,in}$ = 10mg/l

sensitivity. The controller was tuned on the reduced model and its performance on the unreduced model was evaluated using the integral of squared errors (ISE) (see Table 2).

Table 2: Values of the ISE for setpoint Y_S = 0.5 mg/l and Y_S = 7 mg/l in the unreduced and the reduced model

	Y_S = 0.5 mg/l (high sensitivity)	Y_S = 7 mg/l (low sensitivity)
unreduced model	1.07	0.28
reduced model	17.7	0.47

The performance of the reduced model operating in a region of high sensitivity is lower than in the region of low sensitivity. This result is intuitive. However, the ISE is very low in both regions for the unreduced model, so the unreduced model is suitable for tuning in both these regions. What may not be obvious is the reason why for both setpoints, the performance of the controller was better on the unreduced model when it was tuned on the reduced model. This is due to the dampening effect the unreduced model has on the dynamics. The controller requires less control action and hence results in less error. This means that whilst the reduced model is good for tuning, the controller should always be evaluated in the unreduced model to get a more accurate view of its performance.

CONCLUSION

This paper presented a reduced model of an industrial activated sludge process. This was done to increase calculation speed of the simulations for controller tuning. The resulting model reduced simulation time by a factor of 3. So controller tuning can be done more efficiently. The reduced model was validated by examining its sensitivity to the unreduced model. It was clear that at intermediate $S_{P,in}$ the performance of the model is not satisfactory. However, this did not affect the tuning of the controller. The reduced model can be used for tuning purposes over the whole range of $S_{P,in}$.

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BIOGRAPHY

Matty Janssen was born on March 8, 1973 in Weert, The Netherlands. In June 1995 he obtained a Bc. in Chemical Engineering at the Polytechnic College in Eindhoven. After graduating from Wageningen Agricultural University as a Bioprocess Engineer (MSc.) in September 1998, he found his first job as a research assistent at the department of Applied Mathematics, Biometrics & Process Control at Ghent University. There he worked within a government funded project concerning model based control of an industrial WWTP.