# LINEAR PREDICTIVE CONTROL OF A WASTEWATER TREATMENT PROCESS

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Abstract: The paper deals with the control of effluent substrate concentration from a wastewater treatment process described by a nonlinear model. The control variable is the dilution rate. The switching of the operating points and of the linear models of the process is based on the aeration rate value. The contribution of the paper consist in the fact that the effluent substrate concentration is controlled through linear predictive control without using measurements of the substrate, only by measuring the dissolved oxygen concentration, which is most economically.

Keywords: Predictive control, wastewater treatment, dissolved oxygen control, Activated Sludge Process.

## INTRODUCTION

Wastewater treatment processes consist in the separation between some particles and water, aiming to obtain an effluent able to meet the specific EU standards. In general, the operational objective for a wastewater treatment plant is to achieve the required effluent standards with least operational costs (Olsson, *et al.,* 2005). The activated sludge processes are the most generally applied biological wastewater purification technique and attracts a great deal of attention from the research community (Henze, *et al.,* 1997; Vlad, *et al.,* 2011a).

ASP control is a topic widely met in a large number of research studies. Process control of ASPs is a challenging task since the processes are characterized by large disturbances, significant nonlinearities and stiff dynamics. Moreover, many wastewater treatment plants do not have measurement equipments; they have to operate continuously, meeting strict regulations. One of them is to maintain the effluent substrate concentration below the standard limits (20 mg/l) imposed by the European Union (EU Guideline Urban Wastewater Directive 91/271/EEC).

The most popular nonlinear control approach for linear systems is model predictive control (MPC). This method has become the standard for constrained multivariable control problems in the process industries (Caraman, *et al.,* 2007; Holkar and Waghmare, 2010; Mayne, *et al.,* 2000; O'Brien, *et al.,* 2011; Piotrowski, *et al.,* 2008; Shen, *et al.,* 2009). In (Caraman, *et al.,* 2007), predictive control is used to maintain a low concentration of substrate at the output by controlling the dissolved oxygen using the dilution rate as a control variable. The internal model of the process used in predictive control consists in a three layer neural network. Interpolating Model Predictive Control has been employed in (Qin, *et al.,* 1997).

In (Hyunook, *et al.,* 2000) was used a simplified linearized model with aeration time as the manipulated variable. In (Lindberg, 1998) linear multivariable LQ control has been used. In (Wahab, *et al.,* 2006), several multivariable PI control methods are applied to the ASP by linearizing the nonlinear model.

Due to the significant influence of the dissolved oxygen concentration in the aerobic reactors, its control is the most widely-spread in real-life (Chotkowski, *et al.,* 2005; Lindberg, *et al.,* 1996; Sanches and Katebi, 2003). The level of the dissolved oxygen should be sufficiently high to supply enough oxygen to the microorganisms in the sludge, but not excessively high, because it is directly related to the amount of the electrical energy consumption and the sludge quality.

The present work uses a model of the wastewater treatment plant from (Nejjari, *et al.,* 1999). This model plays the role of a real wastewater treatment plant. The aeration rate is considered as the variable that changes the operation point of the process. The wastewater treatment plant operator can establish several levels of aeration rate depending of the level of the influent, based on his expertise. In order to control the level of the substrate concentration from the effluent several operating points were considered to cover the working regimes. In these points, the process was linearized and all these simplified models were used with model based predictive control method.

As it was mentioned above the control objective is to obtain an effluent with a good quality, which is accomplished by the control of the dissolved oxygen concentration considering the dilution rate as control variable.

The paper is organized as follows. Section 2 presents the process description. The third section deals with theoretical considerations regarding the control method used in this paper, while the simulation results are described in the Section 4. Finally, conclusions are drawn.

## MATHEMATICAL MODEL OF THE ACTIVATED SLUDGE PROCESS (ASP)

The mathematical model of the Activated Sludge Process (ASP) considered in this paper has been proposed in (Nejjari, *et al.,* 1999). It is a simplified, highly non-linear model of the wastewater treatment process (WWTP) which was also used in (Vlad, *et al.,* 2011b). The model has four state variables (biomass, substrate, dissolved oxygen and recycled biomass) as follows:

$$(1)\quad \frac{dX}{dt} = \mu(t)X(t) - D(t)(1+r)X(t) + rD(t)X_r(t)$$

$$(2)\quad \frac{dS}{dt} = -\frac{\mu(t)}{Y}X(t) - D(t)(1+r)S(t) + D(t)S_{in}$$

$$(3)\quad \frac{dDO}{dt} = -\frac{K_0\mu(t)X(t)}{Y} - D(t)(1+r)DO(t) + \\ +K_{La}(DO_{\max} - DO(t)) + D(t)DO_{in}$$

$$(4)\quad \frac{dX_r}{dt} = D(t)(1+r)X(t) - D(t)(\beta + r)X_r(t)$$

with

$$(5)\quad \mu(t) = \mu_{\max}\frac{S(t)}{K_s + S(t)}\frac{DO(t)}{K_{DO} + DO(t)}$$

$$(6)\quad K_{La} = \alpha W(t); D(t) = \frac{Q_{in}}{V_a}; r = \frac{Q_r}{Q_{in}}; \beta = \frac{Q_w}{Q_{in}}$$

where $X(t)$ – biomass concentration [mg/l], $S(t)$ – substrate concentration [mg/l], $DO(t)$ – dissolved oxygen concentration [mg/l], $DO_{\max}$ - maximum dissolved oxygen concentration [mg/l], $X_r(t)$ - recycled biomass concentration [mg/l], $D(t)$ - dilution rate [$h^{-1}$], $S_{in}$ and $DO_{in}$ - substrate and dissolved oxygen concentrations in the influent [mg/l], $Y$ - biomass yield factor, $\mu$ - biomass growth rate [$h^{-1}$], $\mu_{max}$ - maximum specific growth rate [$h^{-1}$], $K_S$ and $K_{DO}$ - saturation constants [mg/l], $K_{La}$ - oxygen mass transfer coefficient, α – oxygen transfer rate, $W$ - aeration rate [$m^3$/h], $K_0$ - model constant, $r$ and β - ratio of recycled and waste flow to the influent, $Q_{in}$, $Q_r$, $Q_w$ are the influent, recycle and waste flow rates, respectively. $V_a$ represent the aerator volume.

For complete reference of the WWTP model, equations and assumption see (Barbu, 2007; Caraman, *et al.,* 2007; Nejjari, *et al.,* 1999).

The schematic layout of the wastewater treatment process is represented in Figure 1. In the *Aeration bioreactor* the microorganisms act on organic substrate in order to remove it from the mixture and in the *Settler tank* the solids are separated from the wastewater. A part of the removed sludge is recycled back to the aeration tank and the other part is removed (Katebi, 2003).

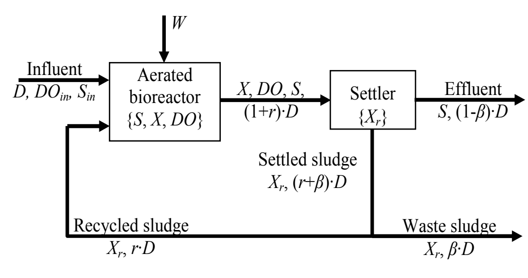


Fig.1. Wastewater treatment process

The model coefficients have the following values: $Y=0.65$; $\mu_{max}=0.15$ $h^{-1}$; $K_S=100$ mg/l; $K_0=0.5$; $\alpha=0.018$; $DO_{max}=10$ mg/l; $\beta=0.2$; $K_{DO}=2$ mg/l; r=0.6. The influent concentrations are set to $S_{in}$ = 200 mg/l and $DO_{in}$ = 0.5 mg/l.

## PREDICTIVE CONTROL

MPC structures are based on the idea of generating values for the process input. These inputs result from an on-line (real time) optimization problem. The structure of MPC strategy is shown in Figure 2.

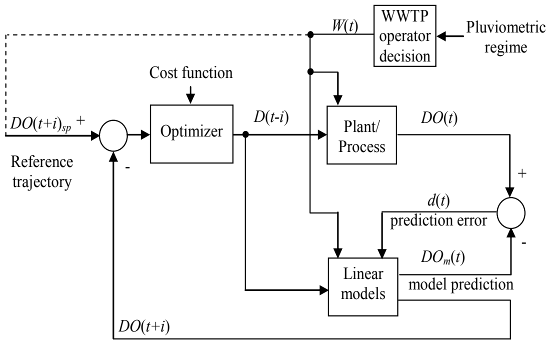


Fig.2. MPC block diagram for dissolved oxygen control

Independent of the model type used in the procedure and of the minimized cost function, the principle of MPC is the same (Camacho and Bordons, 1999). An appropriate model is used to predict the process outputs, $DO(t+i)$, $i=1...N_2$, over a future time interval known as *prediction horizon*, $N_2$. A sequence of control actions, $D(t+i)$, $i=0\ldots N_u-1$, over the *control horizon*, $N_u$, are calculated by minimizing a specified objective which is a function of predicted outputs, $DO(t+i)$, setpoint values, $DO_{sp}(t+i)$ and control actions, $D(t)$. The first control, $D(t)$, of the sequence is implemented and the calculations are repeated for the subsequent sampling periods. In order to account the plant-model mismatch, a prediction error, $d(t)$, that is calculated based on $DO(t)$ measure from the real plant, and model prediction, $DO_m(t)$, is used to update the future predictions.

In (Caraman, *et al.,* 2007) and (Barbu, 2007) only three work regimes were considered: high flow regime (D=1/20 $h^{-1}$, W=80 $m^3/h$), normal flow regime (D=1/35 $h^{-1}$, W=60 $m^3/h$) and low flow regime (D=1/50 $h^{-1}$, W=20 $m^3/h$). In this paper, intermediate regimes are considered. Here, the aeration rate takes the following values: $W$= 20:10:80 $m^3/h$. In all these points the process that has as input $D$ and as output $DO$ was linearized. The linear models of first order have the transfer function given by (7):

$$(7)\quad H(s)=\frac{K}{Ts+1}$$

where $K$ is the static coefficient and $T$ is the time constant. These parameters have the values represented with red markers in Figure 3.

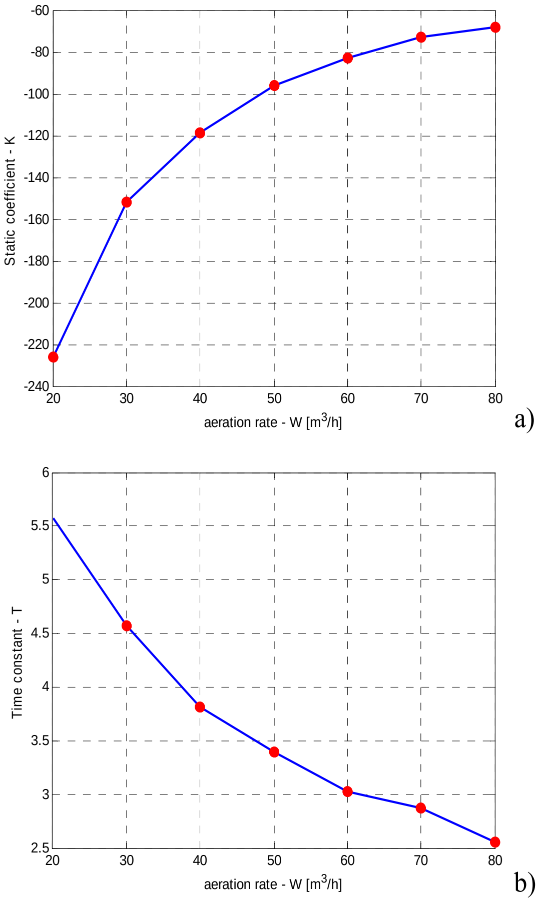


Fig.3. Parameters variations of the linear models of the wastewater treatment process: a) static coefficient; b) time constant

The following predictive controller parameters were used in the simulations: $N_2=5$, $N_u=1$.

## SIMULATION RESULTS

In order to evaluate the performances of the investigated method some simulation results are represented in the following. Figure 4 presents the evolutions of the main variables of the process in case of constant dissolved oxygen setpoint ($DO_{sp}=6.5$). From these results one can see that the substrate concentration from effluent exceeds the maximum value allowable by legislation. The control variable, $D$, has a range between 0.01 and 0.06 $h^{-1}$ which correspond to a water retention time between 100 hours (that is a high value that means a high electrical energy consumption at the aeration pumps) and 16.67 hours.

Off-line tests of the simulated model concluded that using a variable setpoint for the dissolved oxygen concentration, which depends on the schedule variable value ($W$), leads to allowable variations for effluent substrate concentration. Also, at the same time, smaller variations for $D$ are obtained.

The variable setpoint for the dissolved oxygen concentration control loop has the values given in Table 1.

Table 1 DO setpoint values

| $W$ [m$^3$/h] | 20 | 30 | 40 | 50 | 60 | 70 | 80 |
|---|---|---|---|---|---|---|---|
| $DO_{sp}$ [mg/l] | 4 | 5 | 6 | 6.5 | 7 | 7.5 | 8 |

On the basis of the values from Table 1, the equation that gives the dissolved oxygen variable setpoint as a function of the aeration rate was obtained through a polynomial regression.

$$(8)\quad DO_{sp}(W) = 7.5e-6W^3 - 0.0021W^2 + 0.22W + 0.2$$

The results are shown in Figure 5. The operating point of the process can be changed based on the aeration rate. For all these points the measurable dissolved oxygen concentration follows accurately its variable setpoint. In order to validate the proposed solution it must be analyzed the evolution of the substrate concentration. This remains under the maximum standard value for all the operation points.

One can see also that it was obtained a working regime with almost constant dilution rate (around 0.03 h-1). As a consequence, the input flow has small variations, which favors the smooth operation of the aerated bioreactor processes and those from the settler

Further on, considering this variable setpoint for the dissolved oxygen concentration loop, the system robustness for the most important parameter that can influence the effluent quality was studied.

Figure 6 considers a variable dissolved oxygen setpoint and a variable concentration of the substrate in the influent, $S_{in}$. At the moment $t$=170 h $S_{in}$ was changed from 200 mg/l to 300 mg/l and it was kept constant to the new value until $t$=270 h. After that another change was made from 300 mg/l at time $t$=270 h to 150 mg/l and it was kept also constant till $t$=370 h when $S_{in}$ became equal to 200 mg/l. The results from Figure 6 show that the control structures used in this paper rejects perturbation generated by the variation of $S_{in}$ and $DO$ follows the setpoint with small variations when the disturbance is applied. The evolution of the quality variable is kept below the maximum admissible value despite the fact that disturbances up to 50% of the influent substrate concentration were applied.

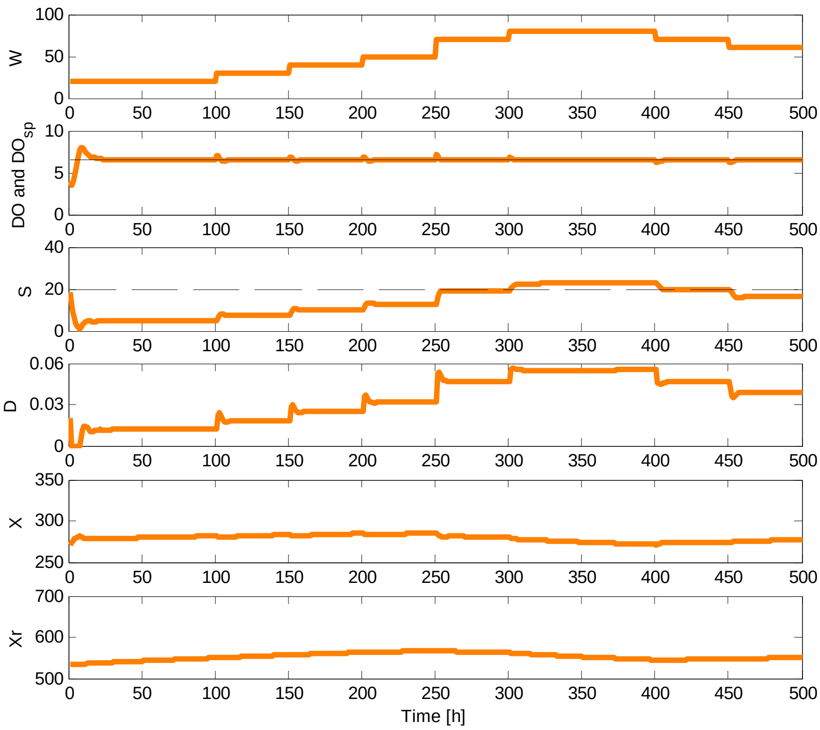


Fig.4. Simulation results for constant dissolved oxygen setpoint ($DO_{sp}$=6.5): aeration rate ($W$), dissolved oxygen concentration ($DO$), substrate concentration ($S$), dilution rate ($S$), biomass ($X$) and recycled biomass concentration ($X_r$)

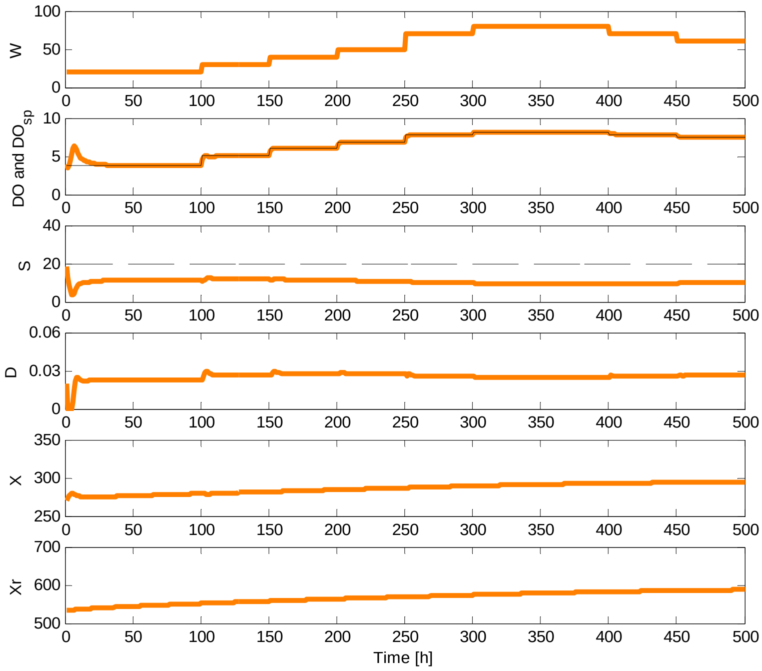


Fig.5. Simulation results for variable *DO* setpoint: aeration rate (*W*), dissolved oxygen concentration (*DO*), substrate concentration (*S*), dilution rate (*S*), biomass (*X*) and recycled biomass concentration ($X_r$)

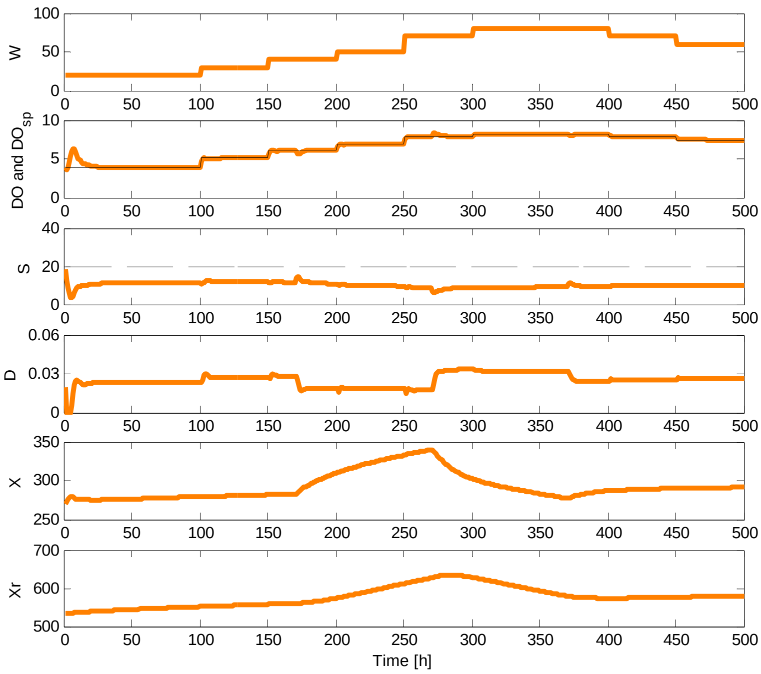


Fig.6. Simulation results for variable *DO* setpoint and variable substrate concentration in influent ($S_{in}$): aeration rate (*W*), dissolved oxygen concentration (*DO*), substrate concentration (*S*), dilution rate (*S*), biomass (*X*) and recycled biomass concentration ($X_r$)

## CONCLUSIONS

In this work, the effluent substrate concentration was controlled through linear predictive control without using measurements of the substrate but only by measuring the dissolved oxygen concentration, which is an economical solution.

The wastewater treatment process was linearized in different operating points considering that its nonlinear model plays the role of a wastewater treatment plant. The method was tested in the case of significant disturbances of the substrate concentration in influent ($S_{in}$). The simulation results have shown a good behavior of the treatment process, an effluent with almost constant flow and quality being obtained. In the same time the substrate concentration in the effluent remains below the maximum values imposed by law (20 mg/l).

This control structure has the advantage of a small computational time. It does not take time for designing the linear controllers for all the operating points, as in the case of gain scheduling method.

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