PID control of the removal of organic component in wastewater treatment plants

[1]Grigore Vlad, [2]Ruben Crişan, [2]Gabriel Harja, [2]Ioan Naşcu

[1] S.C. ICPE Bistriţa S.A., Bistrita, Romania; [2] Faculty of Automation and Computer Science, Technical University of Cluj-Napoca, Cluj-Napoca, Romania.
Corresponding author: G. Vlad, vlad@icpebn.ro

Abstract. Wastewater treatment represents the sum of various processes that reduce pollutant loading to the imposed limits, so that the discharge of the effluent will not damage the environment. If the design of wastewater treatment plant is focused on the removal of organic components, usually this type of plant has primary and secondary treatment. The secondary wastewater treatment – the biological removal of dissolved solids – is a complex process, which needs advanced control strategies for a good operation. This paper presents a systematic procedure to design robust PID controllers to control removal of organic components acting on the aeration air flow rate. The objective of the controllers is to provide adequate effluent quality parameters. The controllers are designed to compensate process parameters variability, to achieve good output disturbance rejection, and to attain good set point response.
Key Words: wastewater treatment, PID control, robust control, wastewater.

Introduction. Wastewater means water that has been used for domestic or industrial purposes. The wastewater is treated before it is allowed to be returned to the environment, lakes, or streams in order to reduce pollutant load. The design of wastewater treatment plant is focused on the removal of organic components. Wastewater treatment plants are complex nonlinear systems, subject to large disturbances, here different physical, chemical and biological phenomena are taking place (Metcalf & Eddy 2003). Those disturbances are due to the complexity of the physical and biochemical phenomena, to the variability of the influent and to the large range of time constants (from a few minutes to several days) inherent in the activated sludge process (Jeppsson 1996). The control of wastewater treatment plants is difficult because of frequent and important changes of load in flow rate and quality and also because of the biological processes which are fundamentals of the plant operation (Nascu et al 2008; Nejjari et al 1999). The use of an appropriate controller permits an optimal functioning at high levels of the parameters, closer to the maximum allowed values specified in legal provisions, leading to a lower specific energy consumption and higher efficiency.

PID control has been the state of the controller art since the 1950's and is still the predominant method in use today. Their popularity is justified by the following advantages: a simple structure, the control principle is well understood by instrumentation engineers and the control capabilities have proven to be adequate for most control loops. PID controllers, although having a simple structure, are by far the most used controllers in control systems (CE Staff 1998; Astrom & Hagglund 1995). They can be found in both categories of systems resulted from developing technologies and automation and control systems products: DCS and PLC. In a study published in 2001 (Astrom & Hagglund 2001) authors state that, in the industrial applications, more than 90% of the control loops are PID control based. This paper concentrates on the much used PID controller, but tuned using robust considerations, analyzing by simulation the achievable performance and limitations of this simple controller. The controller is designed to compensate for process model parameters variability (uncertainty), to achieve good output disturbance rejection, and to attain good set point response.

This paper is structured as follows: the mathematical model is briefly described in the next section, followed by the controller design method presented in section III. The results of closed loop control are presented in section IV, and the conclusions are summarized in the final section.

Process model. Most wastewater is treated in industrial-scale energy intensive Wastewater Treatment Plants (WWTPs) which include physical, chemical and biological treatment processes. If the design of WWTP is focussed on the removal of organic components, usually those types of plants have primary treatment (physical removal of floatable and settleable solids) and secondary treatment (the biological removal of dissolved solids) (Figure 1).

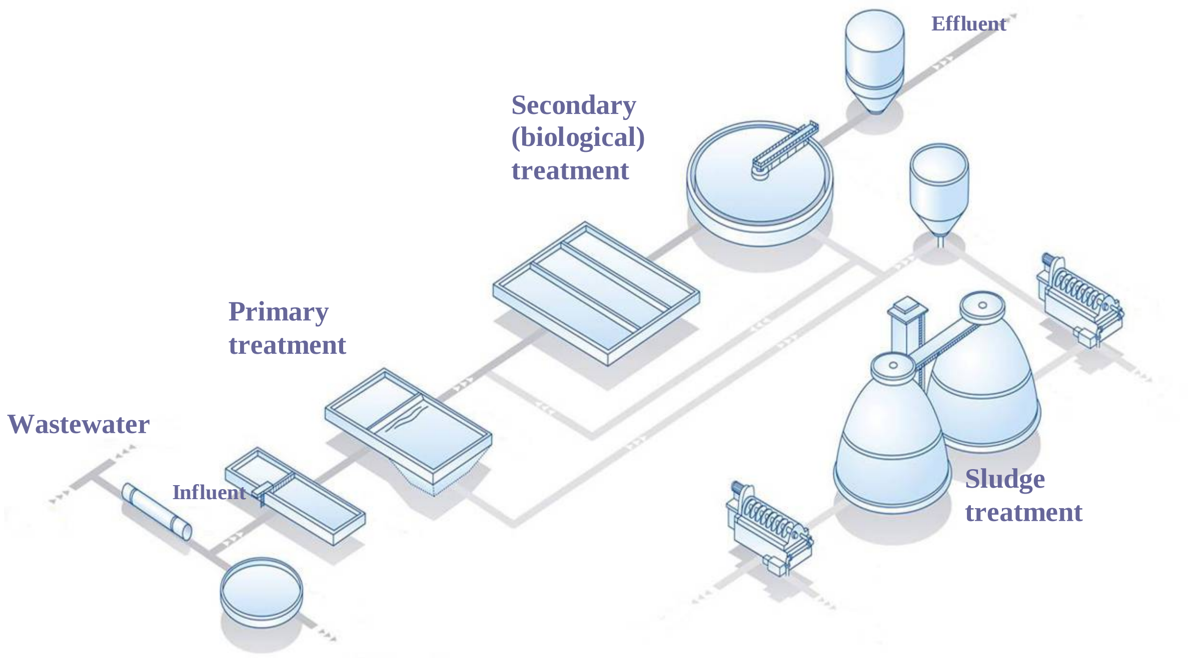

Figure 1. Wastewater treatment plant structure.

The secondary wastewater treatment - the biological removal of dissolved solids - is a complex process, which needs advanced control strategies for a good operation. Figure 2 presents the schematic representation of the biological part of wastewater treatment process. The most common option uses microorganisms in the treatment process to break down organic material with aeration and agitation and then allows solids to settle out. The process is principally constituted by two sequential tanks, an aerated tank and a settler. In the aerated tank the bacteria and other microorganisms feed on the organic matter constituent of the incoming wastewater in the presence of air, thereby reducing the strength of the waste.

The clarifier tank or settler is a gravity settlement tank where the sludge and the clear effluent are separated. A part of the settled sludge is recycled as return activated sludge from the clarifier to the aeration reactor so that the microorganism content in the reactor is maintained at the reaction sustenance level. Excess sludge is extracted from the system.

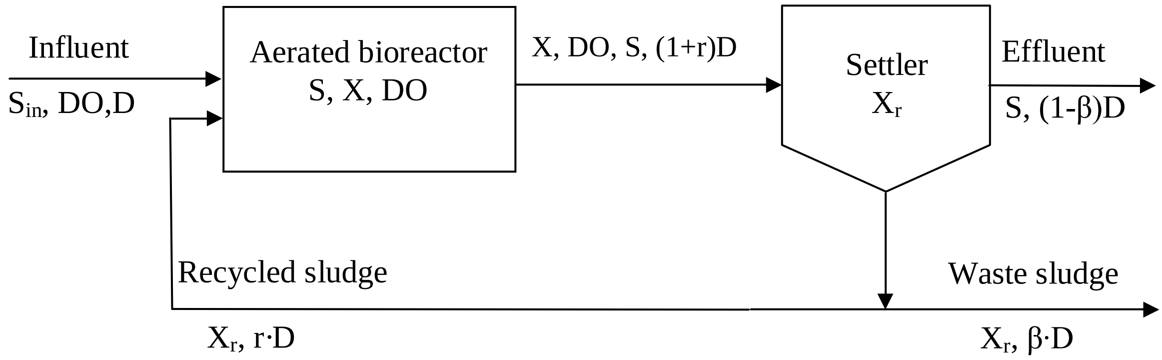

Figure 2. Biological process structure.

The wastewater treatment systems are complex, non-linear processes, with multiple inputs and outputs. This paper considers a simplified model of the biological wastewater treatment plant (Jeppsson 1996; Nascu et al 2008; Nejjari et al 1999). The model is based on the following assumptions: the aerator is considered to be perfectly mixed; no bioreaction takes place in the settler and the sludge is the only recycled component into the aerator; the oxygen and substrate concentrations are neglected in the recycled stream; the output flow of the aerated tank is equal to the sum between the output flow of the settler and the recycled sludge flow.

The mass balance around the aerator and the settler gives a set of four non-linear differential equations.

The first equation is related to the balance of the active sludge at the level of the aeration tank:

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

The second equation is related to the mass balance of the substrate:

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

The third equation is related to the mass balance of the oxygen in the water mass, the oxygen consumed by the bio-chemical degradation of the organic matters, the oxygenation process performed by the oxygen transfer from the air supplied with specific equipment in the water:

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

The fourth equation is related to the balance of the active sludge at the level of the settling tank:

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

In the above equations, the following notations were used: $X(t)$ - biomass, $S(t)$ - substrate, $DO(t)$ - dissolved oxygen, DO_{max} - maximum dissolved oxygen, $X_r(t)$ - recycled biomass, $D(t)$ - dilution rate (the ratio of influent flow to the aerated bioreactor's volume), S_{in} and DO_{in} - substrate and dissolved oxygen concentrations in the influent, Y - biomass yield factor, α - oxygen transfer rate, W - aeration rate, K_0 - model constant, r - the ratio of recycled flow to influent flow, β - the ratio of waste flow to influent flow. The biomass growth rate μ – is a complex function of many physical, chemical and biological factors. Many different analytical laws have been suggested for modeling this parameter. The most popular one is the Monod law but here we assume that μ depends on substrate, dissolved oxygen concentrations and several kinetic parameters (Olsson model (Olsson 1976)):

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

where μ_{max} represent the maximum specific growth rate, K_S - affinity constant, expressing the dependency of the degradation rate on the concentration of pollutant S and K_{DO} – saturation constant.

Controller design. The PID controller is one of the most common algorithms used in control systems. It is described by the following relation:

$$u(t) = K\left(e(t) + \frac{1}{T_i}\int_0^t e(t)dt + T_d\frac{de(t)}{dt}\right) \tag{6}$$

where *u* is the control signal, *e* is the error (difference between the measured signal and setpoint), *K*, T_i and T_d are the controller parameters known as: proportional gain, integral time and derivative time. The control signal is therefore a sum of three terms: P term (proportional to the error, handles the current error), I term (proportional to the integral of the error) and D term (proportional to the derivative of the error).

Tuning a PID controller means setting the parameters so that the weighted sum of the proportional, integral, and derivative terms produces a controller output that drives the process variable to the desired target. The parameters can be tuned using mathematical methods or controller design tool. The aim of the tuning is to obtain fast response and good stability.

In this paper a PID controller used for the substrate concentration control was designed using FR-tool, a Computer Aided Design (CAD) software that uses frequency response techniques (De Keyser & Ionescu 2006). FR-tool is an interactive design tool based on design specifications like: robustness, settling time, overshoot, and gain and phase margins. These specifications are converted into graphical restrictions of the Nichols diagram (Figure 3 left). By applying Laplace transform to relation (6), the PID controller transfer function can be written in the pole-zero form:

$$C(s) = K + \frac{K_i}{s} + K_d s = \frac{K_d s^2 + Ks + K_i}{s} = \frac{K_p(s - z_1)(s - z_2)}{s} \tag{7}$$

FR-tool tuning parameters are: gain, zeros and poles. The transfer function of the PID controller has one pole at the origin and two zeros. Gain can be tuned using the K_p field from Figure 3 left or by changing the bandwidth frequency (dragging the small circle displayed on Nichols curve of the open loop system). Controller zeros were tuned using drag&drop feature available in the design window (Figure 3 right).

Given the maximum overshoot, the damping factor ζ can be calculated using the formula below:

$$OS = e^{-\frac{\pi\zeta}{\sqrt{1-\zeta^2}}} \tag{8}$$

Knowing the damping factor, the peak value of the closed-loop frequency-domain magnitude can be obtained, as following:

$$M_r = \frac{1}{2\zeta\sqrt{1-\zeta^2}} \tag{9}$$

The peak value is represented graphically by an outside continuous line curve in (Figure 3 left). For higher overshoot the curve becomes smaller. To fulfill the design specifications, the Nichols curve of the open loop system has to be outside of (or tangent to) this outside continuous line curve (http://dea.unsj.edu.ar/control2/guia.pdf). Another design specification is settling time, displayed as a small circle on the Nichols curve. This circle has to be above the -3dB line (continuous line). Robustness specification is represented by a blue circle on the Nichols plot. Similar to the overshoot, to fulfill the robustness specifications, the Nichols curve has to stay outside the blue circle. Besides these 3 restrictions, gain and phase margins specifications can be used, but were not considered in this study.

The PID design procedure consists in playing with the 2 zeros of the transfer function (7) so that the controller proportional gain K_p is as large as possible, to reduce the settling time, but still satisfying the required specification for overshoot and a relatively high robustness.

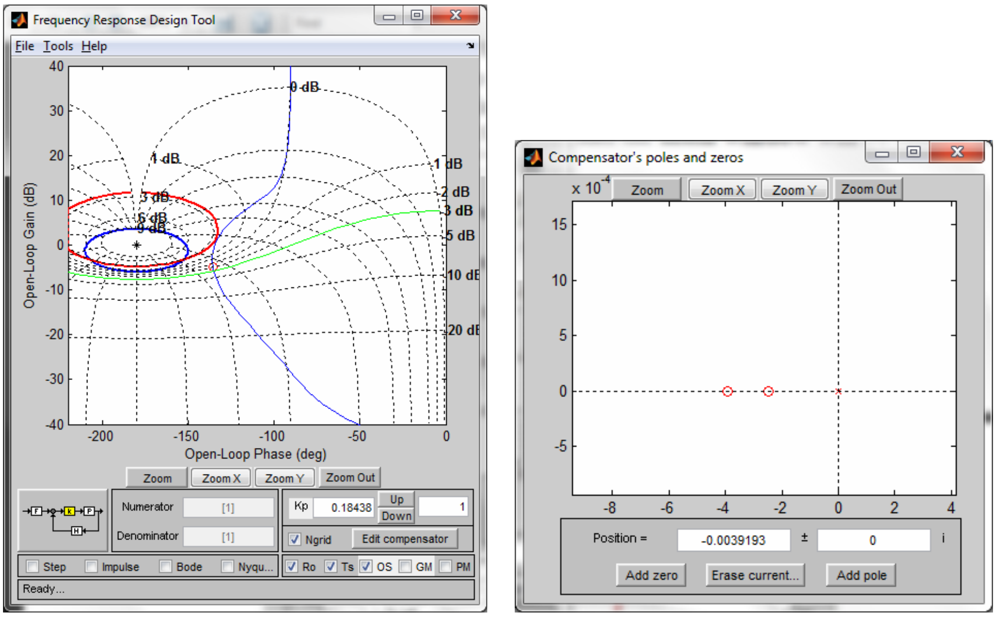

Figure 3. PID design with FR-tool.

Simulations. Although the process is inherently multiple input multiple output (MIMO), the different time constants of a wastewater treatment system (ranging between minutes for DO dynamics to days for the sludge composition), allows to decouple the many control actions into separate single input/single output (SISO) controllers.

The diagram from Figure 4 shows Matlab Simulink block implementation of nonlinear process model.

Simulations results were obtained by using the following values for the model coefficients kinetic parameters and inputs: Y = 0.65; β = 0.2; α = 0.018; K_{DO} = 2mg/l; K_0 = 0.5 μ_{max} = 0.15mg/l; K_S = 100mg/l; DO_{max} =10mg/l; r = 0.6 respectively DO_{in} = 0.5mg/l; S_{in} = 200mg/l; D=0.05 1/h and W=80m3/h. Analyzing the response of the substrate concentration (S) for a step of the aeration rate (W) we notice that this is the characteristic response of a second order system. Linearizing the model of the nonlinear system under study around an operating point to design a controller, it is clear that a deviation in the operating point results in a modification of the linear model parameters. The linear model was used in the form of transfer function.

In this work, the dilution rate (D) is considered to be the factor that perturbs the process. It is assumed that the dilution rate, which is the ratio of influent flow to the aerated bioreactor's volume, has the possible variation values comprised in the [0.05; 0.15] interval.

For each value of the perturbation D, the nonlinear model has been brought to stationary values in order to compare the evolution of the output (S) according to a step signal given on the input (W), both for the linear and nonlinear systems. The linear model used to approximate the nonlinear one, consists of a parallel connection of two first order transfer functions having the proportional gain as k_{p1} and k_{p2} and the time constants as t_{p1} and t_{p2}. Table 1 shows the parameter values obtained for a series of changes in the perturbation D. From these values results a family of transfer functions.

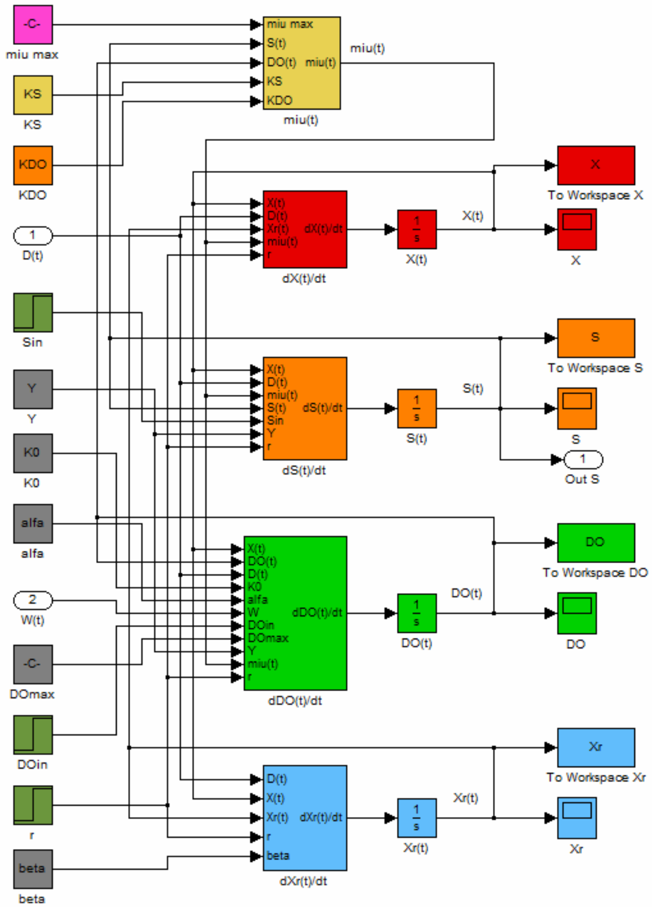

Figure 4. Nonlinear process implementation.

Table 1

Linear model parameters for the input S and output W

kp1=.02	kp2=.00395	tp1=3.5	tp2=164	D=0.05
kp1=.031	kp2=.0081	tp1=3.5	tp2=152	D=0.06
kp1=.043	kp2=.0159	tp1=3.5	tp2=142	D=0.07
kp1=.054	kp2=.028	tp1=3.5	tp2=132	D=0.08
kp1=.063	kp2=.043	tp1=3.5	tp2=135	D=0.09
kp1=.065	kp2=.0625	tp1=3.5	tp2=132	D=0.1
kp1=.06	kp2=.0825	tp1=3.5	tp2=138	D=0.11
kp1=.0515	kp2=.0975	tp1=3.5	tp2=157	D=0.12
kp1=.038	kp2=.1074	tp1=3.5	tp2=183	D=0.13
kp1=.0245	kp2=.1085	tp1=3.5	tp2=231	D=0.14
kp1=.0145	kp2=.0962	tp1=3.5	tp2=348	D=0.15

The responses of the linear models obtained for different values of the perturbation *D* were used in a comparison with the nonlinear system response resulting in a similar trajectory. In order to illustrate this outcome, simulations were performed considering the perturbation *D* = 0.15. The comparative graphics for linear and nonlinear systems are represented in Figure 5.

Having the linear model parameters determined for all the 11 operating points it was performed the tuning of the PID controller parameters using the Computer Aided Design (CAD) software - FR-tool. The performances of the closed-loop system have been chosen as following: maximum response time – 6 hours, no overshoot and robustness – 0.5.

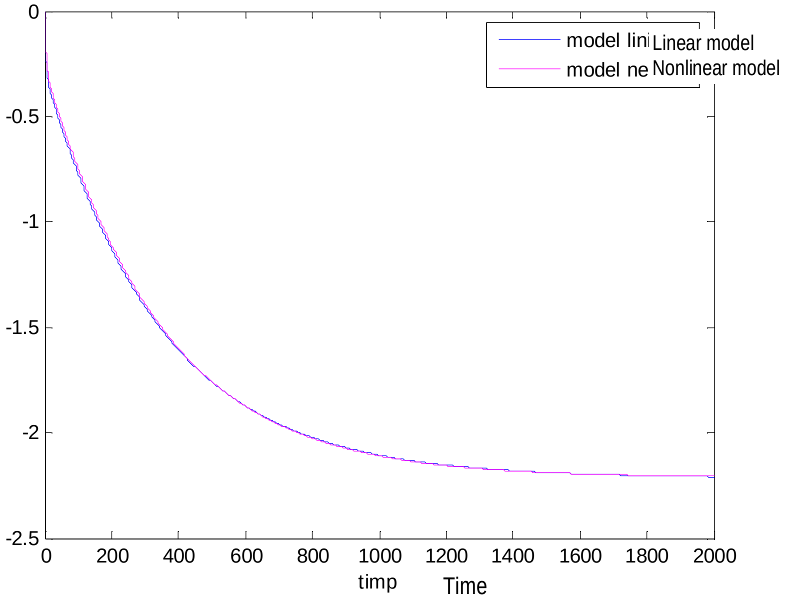

Figure 5. The step response of the systems for perturbation D = 0.15.

In Figures 6 and 7 Matlab Simulink implementations of PID control using linear and nonlinear model are shown.

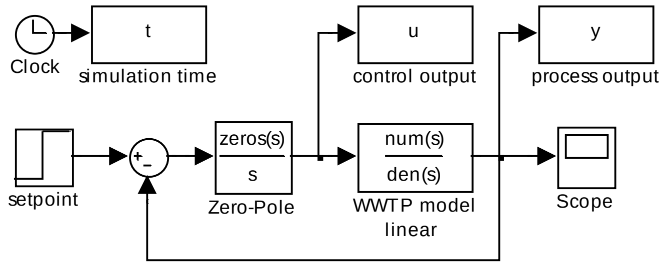

Figure 6. PID control of the process. Linear process model.

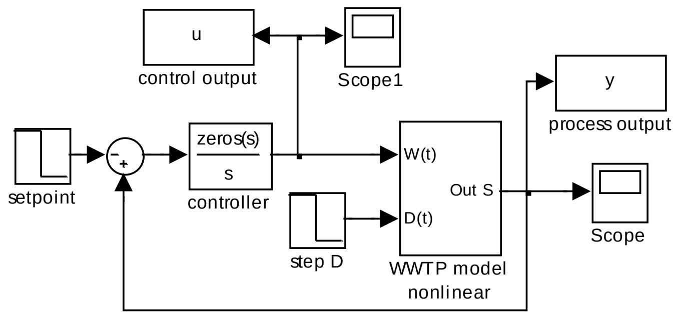

Figure 7. PID control of the process. Nonlinear process model.

Thus, the result is a robust PID controller which will satisfy the imposed performances for any value of the dilution rate (*D*) comprised in the mentioned interval. In Figure 8 it is shown that the linear model family (different values of *D*) fulfils the design specifications. A final comparison is made, revealing the almost identically response of the closed-loop linear and nonlinear model for D = 0.05. The plot is displayed in Figure 9.

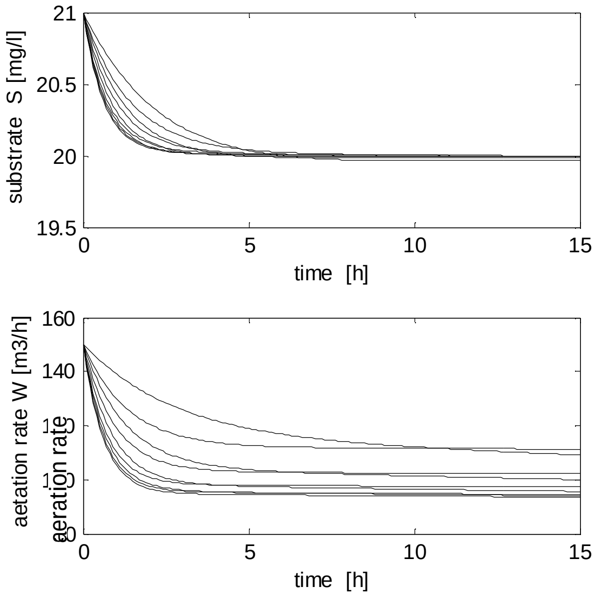

Figure 8. Simulation results using linear model and different values of D.

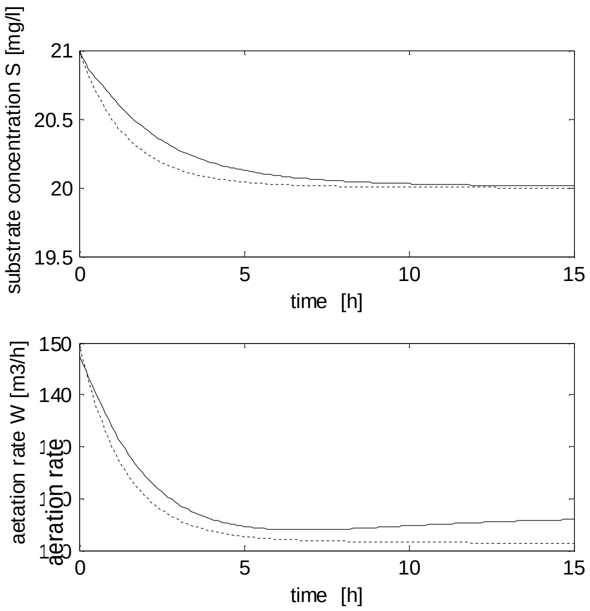

Figure 9. Comparison between closed-loop linear and nonlinear systems.

Conclusions. The purpose of this paper was to use a PID to control the output pollutant substrate concentration. A wide range of parameter changes and nonlinearities of the plant can be handled using the much used PID controller, but tuned using robust considerations. The controller is designed to compensate for process model parameters variability (uncertainty), to achieve good output disturbance rejection, and to attain good set point response. Simulation studies were based on direct exploitation of the non-linear wastewater treatment dynamical model, obtained from mass balance equations and they have indicated that the presented method performs well and can be easily used.
ACKNOWLEDGMENT

Acknowledgements. This paper is supported by Partnerships in priority domains Program – PN-II-PT-PCCA-2013-4.

References

Astrom K. J., Hagglund T., 1995 PID controller: theory, design and tuning; 2nd Edition. Instrument Society of America.

Astrom K. J., Hagglund T., 2001 The future of PID control. Control Engineering Practice 9(11):1163-1175.

CE Staff, 1998 Single-loop controllers dominate marketplace; Control Engineering.

De Keyser R., Ionescu C., 2006 FR-tool: a frequency response tool for CACSD in Matlab. IEEE - Computer Aided Control System Design, Munich, Germany, pp. 2275–2280.

Jeppsson U., 1996 Modelling aspects of wastewater treatment processes. PhD thesis, Dept. of Industrial Electrical Eng. and Automation, Lund University, Sweden.

Metcalf and Eddy, Inc., 2003 Wastewater engineering: treatment and reuse; 4th Edition. McGraw-Hill, New York, 1819 pp.

Naşcu I., De Keyser R., Vlad G., Nascu I., 2008 Modelling and control aspects of wastewater treatment processes. Ecoterra 18:27-29.

Nejjari F., Benhammou A., Dahhou B. Roux G., 1999 Non-linear multivariable adaptive control of an activated sludge wastewater treatment process. Int J Adapt Control Signal Process 13:347-365.

Olsson G., 1976 State of the art in sewage treatment plant control. A. I. Ch. E. Symp. Ser. 72:52-76.

*** http://dea.unsj.edu.ar/control2/guia.pdf

Received: 07 November 2014. Accepted: 29 November 2014. Published online: 30 December 2014.
Authors:
Grigore Vlad, S.C. ICPE Bistrita S.A., 7, Parcului Street, 420035 Bistrita, Romania, e-mail: vlad@icpebn.ro
Ruben Crişan, Faculty of Automation and Computer Science, Technical University of Cluj-Napoca, George Baritiu str., no. 26-28, 400027 Cluj-Napoca, Romania, e-mail: Ruben.Crisan@aut.cutcluj.ro
Gabriel Harja, Faculty of Automation and Computer Science, Technical University of Cluj-Napoca, George Baritiu str., no. 26-28, 400027 Cluj-Napoca, Romania
Ioan Naşcu, Faculty of Automation and Computer Science, Technical University of Cluj-Napoca, George Baritiu str., no. 26-28, 400027 Cluj-Napoca, Romania, e-mail: Ioan.Nascu@aut.utcluj.ro

How to cite this article:
Vlad G., Crisan R., Harja G., Nascu I., 2014 PID control of the removal of organic component in wastewater treatment plants. Ecoterra 11(4):23-31.