Model-Based Optimization of an Anaerobic Digestion Process

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Abstract—This paper deals with the optimization of an anaerobic digestion process considering aspects regarding both the economic benefit, expressed through the biogas production, as well as environmental issues, expressed through the quality of the discharged water. The adopted method involves determining the optimal regimes characteristics obtained based on a mathematical model. The optimal set point of the water quality loop, expressed by the Chemical Oxygen Demand, is computed as a function of the influent substrate concentration. The water quality loop includes a robust control solution based on the Quantitative Feedback Theory, thus incorporating the parametric uncertainties that affects this type of processes.

Keywords—Anaerobic digestion, model-based optimization, robust control.

I. Introduction

The modern society relies upon the treatment of wastewater before it is discharged. The usual treatment solution is aerobic [1], [2], [3], [4] but this implies a high economic cost determined, mainly, by the energy consumption for aeration. The use of anaerobic digestion technology allows the treatment of an influent with a very high organic load and, at the same time, leads to an economic benefit through the resulting biogas. Thus, this technology has become more popular, being used independently for both the treatment of influents and in urban aerobic wastewater treatment plants for the treatment of the resulted sludge and the high-load influent.

Anaerobic digestion is a multi-stage biological wastewater treatment process whereby several functional groups of bacteria decompose organic matter in the absence of oxygen through a series of physicochemical and biochemical reactions and produce carbon dioxide and usable methane [5]. The most complex model is called anaerobic digestion model (ADM1) and includes 32 state variables [6].

For the implementation of control solutions, simplified models have been proposed over time [7], [8], [9]. The usual control solutions adopted for anaerobic digestion processes refers to either robust control techniques [10], or optimization control techniques using extremum seeking method [11], [12]. In [13] there is an exhaustive presentation of the state of the art regarding the instrumentation and control of the anaerobic digestion processes.

A method of control applied to anaerobic digestion processes is model-based optimization [14]. The method involves determining the optimal regimes characteristics obtained based on a mathematical model. The optimal setpoint of the dilution rate is computed as a function of the influent substrate concentration. But this approach has the main drawback that it leads to the problem of dilution rate control, when in fact the dilution rate is the manipulated variable used in the anaerobic digestion process. Furthermore, the method considers a perfect model without considering the parametric uncertainties that affects the biotechnological processes. In these conditions, in this paper model-based optimization is considering that the setpoint to be extracted from the optimal regime characteristics is the water quality, and the water quality control loop is treated considering a robust approach that also takes account the parametric uncertainties inherent to this type of process.

The paper is structured as follows: the next section presents the model of the anaerobic digestion process. Section 3 presents the design of the robust control solution and Section 4 contains the model-based optimization of the process. Finally, the last section is devoted to the conclusions.

II. Mathematical Modeling of The Anaerobic Digestion Process

In this paper, a simplified dynamic model is used whose parameters have been identified using data obtained by simulating the ADM1 complete model [6]. The simplified model was proposed in [9] and is given by the following differential equations:

$$\dot{X}_1 = \mu_1 X_1 - \alpha D X_1 \quad (1)$$

$$\dot{S}_1 = -k_1 \mu_1 X_1 + k_2 \mu_2 X_2 + D\left(S_{1,in} - S_1\right) \quad (2)$$

$$\dot{X}_2 = \mu_2 X_2 - \alpha D X_2 \quad (3)$$

$$\dot{S}_2 = k_3 \mu_1 X_1 - k_4 \mu_2 X_2 + D\left(S_{2,in} - S_2\right) \quad (4)$$

where X_1 are the acidogenic microorganisms, X_2 are the acetogens and methanogens, S_1 is the organic matter and S_2 represents the organic acids. Also: $D = F_{in,d} / V_d$ is the dilution rate, $F_{in,d}$ is the pollutant influent flow rate, V_d is the digester volume, μ_i, $i = 1, 2$, is the specific growth rate of the reaction i, k_i (i = 1,...,4) are yield coefficients, $S_{1,in}$ and $S_{2,in}$ are the influent substrate concentrations and α gives the nature of the reactor.

Also, the Monod type of growth rates are attached to this model: $\mu_1 = \mu_1^0 S_1 / (K_{S_1} + S_1)$ and $\mu_2 = \mu_2^0 S_2 / (K_{S_2} + S_2)$, where μ_1^0 and μ_2^0 represents the maximum growth rates and K_{S_1} and K_{S_2} are saturation constants. Finally, the equation given the biogas production rate is attached to the model [9]:

$$q_{CH_4} = \beta_1 \mu_1 X_1 + \beta_2 \mu_2 X_2 \quad (5)$$

where β_1 and β_2 are proportional constants for the first and second reactions, respectively.

For this process we will consider the dilution rate, D, as the manipulated variable, and as controlled variable we will consider the effluent quality expressed by the Chemical Oxygen Demand, $COD = S_1 + S_2$. We will also consider the influent quality as a disturbance, $COD_{in} = S_{1,in} + S_{2,in}$.

For designing a linear control structure, taking into account the nonlinear character of the process, the nonlinear model has been linearized around one operating point given by the control variable $D = 0.1\, day^{-1}$ and the influent $COD_{in} = 1.93\, KgCOD / day$, corresponding to influent variables: $S_{1,in} = 1.89\, KgCOD / day$ and $S_{2,in} = 0.04\, KgCOD / day$. Linearization was performed using the Matlab function *linmod*, resulting the following transfer function:

$$P_{D-COD}(s) = \frac{1.8679(s+19.22)(s+0.05)(s+0.04987)}{(s+21.76)(s+2.464)(s+0.04988)(s+0.04896)} \quad (6)$$

From equation (6) it can be seen that the transfer function obtained can be simplified and brought to the form:

$$P_{D-COD}(s) = \frac{1.9072(s+19.22)}{(s+21.76)(s+2.464)} \quad (7)$$

The linearization process was done considering the following factors that can affect the anaerobic digestion process: the variation of the nominal operating point given by the command D, but also the disturbances $S_{1,in}$ and $S_{2,in}$; parametric uncertainties that affects the nonlinear model, taking into account the known variability of biotechnological processes. Finally, the nonlinear process can be described by a linear model with variable parameters, the parameters variation limits being determined in accordance with the above-mentioned aspects. The transfer function results as follows:

$$P_{D-COD}(s) = \frac{K(s+a)}{(s+b)(s+c)} \quad (8)$$

with: $K \in [1.9 \quad 2.5]$, $a \in [14 \quad 20]$, $b \in [18 \quad 23]$ and $c \in [0.8 \quad 2.5]$.

III. QFT Control of The Anaerobic Digestion Process

A method used to control processes described by linear models with variable parameters is the robust control method entitled Quantitative Feedback Theory (QFT) [15]. For the QFT method, the scheme given in Figure 1 is used [16]. A compensator, $G(s)$, and a prefilter, $F(s)$, are designed so that the closed loop system behavior falls within the performance area imposed for the system with variable parameters, $P(s)$, as shown in Figure 2.

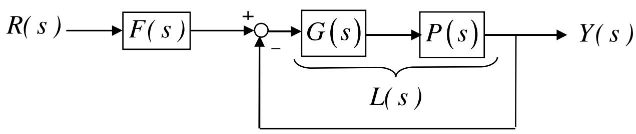

Fig. 1. System scheme used for the QFT method

To ensure the stability of the closed-loop system, it is desirable that, in the considered frequency band, the closed loop transfer gain characteristics do not exceed an upper limit value:

$$\left|H_0\right| = \left|\frac{GP}{1+GP}\right| \le M_L \quad (9)$$

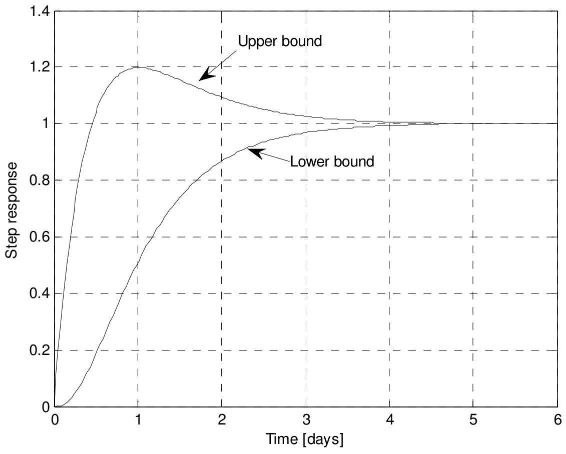

Fig. 2. Performance area accepted for closed-loop system

To ensure the tracking properties of the system, the lower and upper boundaries are defined in which the closed loop output, $y(t)$, should fit. In the case of the anaerobic digestion process given by the linear model with variable parameters from equation (8), was imposed $M_L = 1.2\,dB$ and the lower and upper tracking models are given by the transfer functions presented below, the step response of which are shown in Figure 2:

$$H_L(s) = \frac{37.5}{(s+10)(s+2.5)(s+1.5)} \tag{10}$$

$$H_U(s) = \frac{4(s+0.8)}{(s+2)(s+1.6)} \tag{11}$$

For the design of the controller and the prefilter the Matlab QFT Control Toolbox, QFTCT [17], was used. In Figure 3 is presented the synthesis of the $G_{D-COD}(s)$ controller on the Nichols characteristics, and in Figure 4 is presented the synthesis of the prefilter $F_{D-COD}(s)$ on the Bode characteristics. The numerical results obtained for the controller and the prefilter are:

$$G_{D-COD}(s) = \frac{38.3333(s+1.2)}{s(s+11.5)} \tag{12}$$

$$F_{D-COD}(s) = \frac{2.5263(s+0.95)}{(s+2)(s+1.2)} \tag{13}$$

Using the same QFTCT toolbox, the two considered properties have been checked: stability and tracking. Thus, Figure 5 gives the result of checking the imposed stability condition, $M_L = 1.2\,dB$. This figure shows that this is respected for all frequencies considered. In terms of checking the tracking properties, Figure 6 gives the time domain simulation for the linear model with variable parameters with the designed QFT structure and the two imposed limits. As all the step responses stands between the two imposed limits, we can use this control structure also for the nonlinear process.

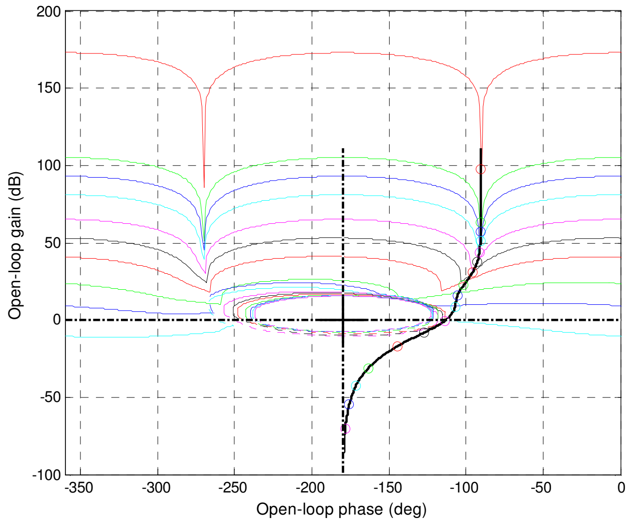

Fig. 3. Design of the controller $G_{D-COD}(s)$

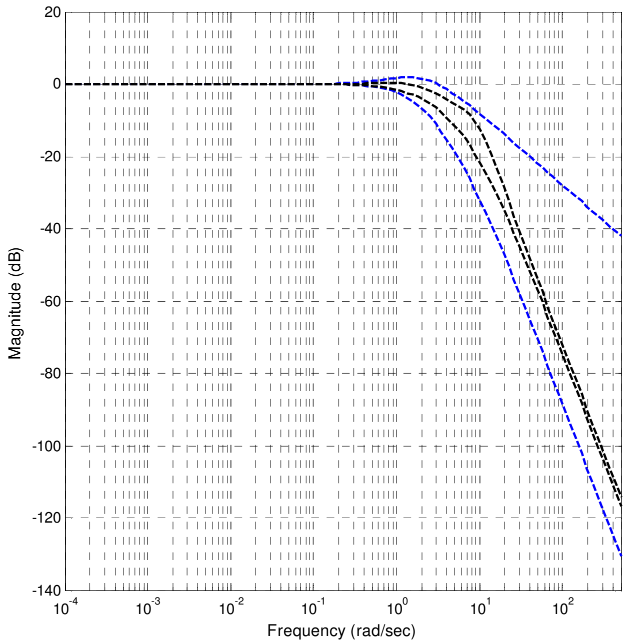

Fig. 4. Design of the prefilter $F_{D-COD}(s)$

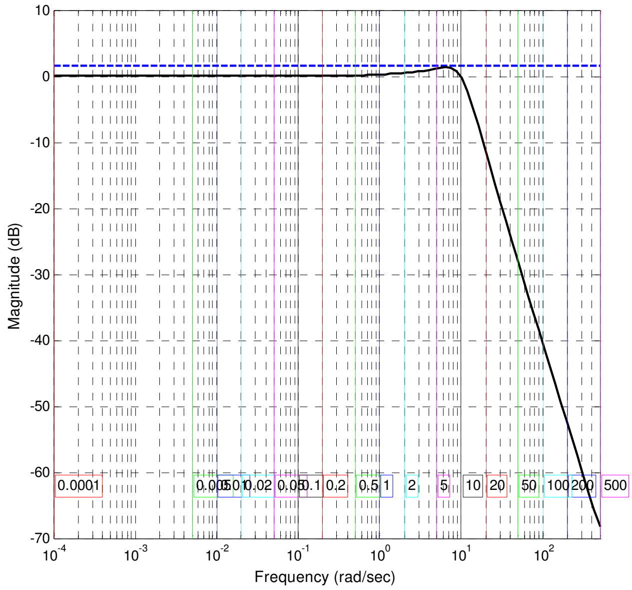

Fig. 5. The stability condition checking

Finally, the designed control structure was tested on the nonlinear process given by the equations (1)-(4). Thus, Figure 7 shows the evolution of the controlled variable, *COD*, for different setpoints and of the manipulated variable, *D*. It can be seen from the figure that for all the nominal operating points considered, generated by the setpoint variations, the closed-loop system follows the required setpoint, the quality of the loop response being included within the limits considered for the design.

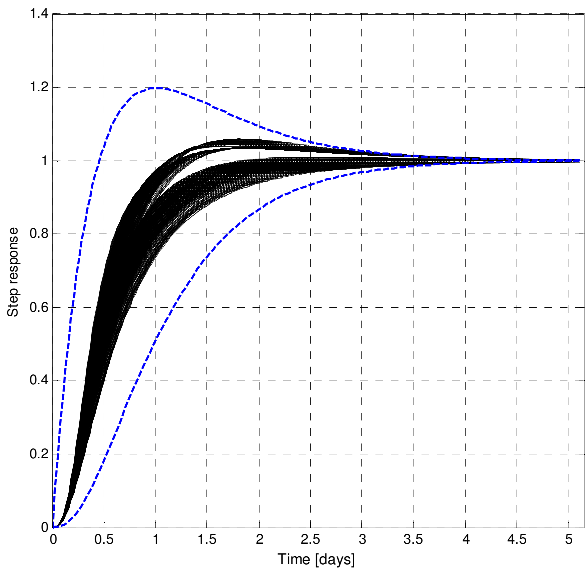

Fig. 6. Simulation of the proposed control structure considering the linear model with variable parameters (8) (dotted lines - imposed limits, continuous lines - simulation results)

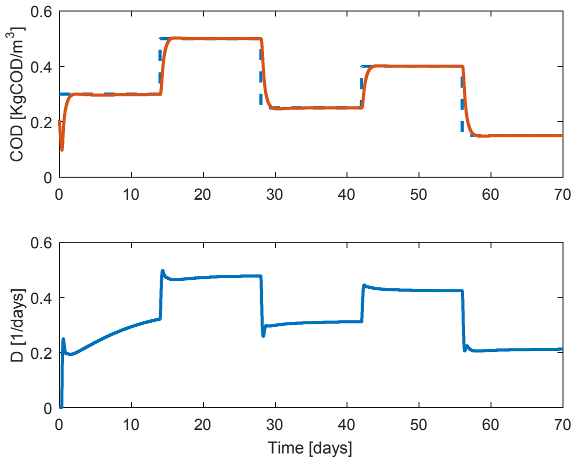

Fig. 7. Simulation of the proposed control structure considering the nonlinear model: a) system output response, *COD*, in the case of a sequence of setpoint steps (dotted blue – setpoint; continuous red – output variable); b)) evolution of manipulated variable, *D*.

IV. MODEL-BASED OPTIMIZATION OF THE ANAEROBIC DIGESTION PROCESS

The anaerobic digestion process has as its main purpose the treatment of wastewater, one of the benefits being the production of biogas. Under these conditions, the following optimization problem can be formulated, incorporating both requirements:

$$\max_D J = \max_D \left(q_{CH_4} + \gamma \cdot COD_{ef} \right) \tag{14}$$

where COD_{ef} expresses the quality of the effluent, and the parameter γ must be negative. Thus, the optimization problem was formulated to maximize methane production and to have a limitation of the environmental impact through the effluent from the anaerobic digestion plant. The term γ gives the weighting of the water quality criterion in relation to the economic benefit from the biogas production.

In Figure 8 is presented the evolution of the optimization criterion *J* with respect to the setpoint applied to the control system designed in the previous section, COD_{sp} , for different values of the quality of the influent, COD_{in} . From the figure we can see that the maximum value of the criterion *J* depends on the COD_{in} . The optimal regime characteristics (ORC) of the process is the function $COD_{sp} = f\left(COD_{in}\right)$, where for COD_{sp} we obtain the maximum value of criterion *J* when the influent quality is COD_{in} . Thus, based on the model given by equations (1) - (5) and considering the quality of the influent, COD_{in} , we can determine at any moment the optimal value of the setpoint for the *D-COD* control loop.

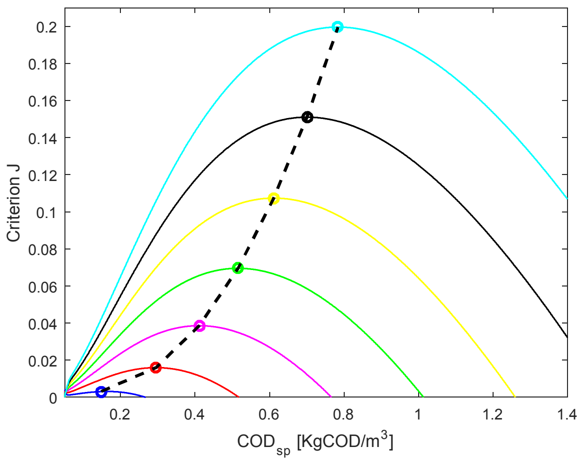

Fig. 8. Evolution of criterion *J* with respect to COD_{sp} for different values of COD_{in} and optimal regime characteristics (blue: COD_{in} =0.965; red: COD_{in} =1.4475; magenta: COD_{in} =1.93; green: COD_{in} =2.4125; yellow: COD_{in} =2.895; black: COD_{in} =3.3775; cyan: COD_{in} =3.86).

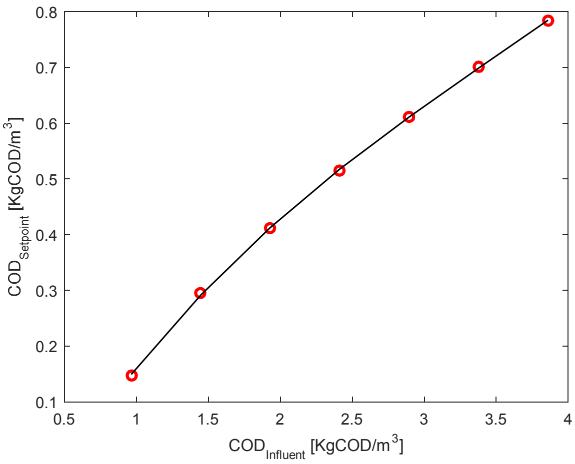

Fig. 9. Dependency $COD_{sp} = f\left(COD_{in}\right)$: red dots: measured points; continuous line: polynomial approximation.

Based on the optimal regime characteristics we can determine the curve $COD_{sp} = f\left(COD_{in}\right)$. Further, the function *f* was approximated by a polynomial function, given by:

$$
\begin{aligned}
COD_{sp} &= 0.0074 \cdot COD_{in}^3 - 0.0777 \cdot COD_{in}^2 + \\
&+ 0.4494 \cdot COD_{in} - 0.2186
\end{aligned}
\tag{15}
$$

valid for $COD_{in} \in [0.965, 3.86]\ KgCOD / m^3$.

Finally, the proposed control structure, containing the solution for optimal determination of the setpoint for the *D-COD* loop and the designed QFT robust control solution, was tested using the non-linear model of the anaerobic digestion process. The results obtained are presented in Figures 10-12, where are graphically represented the evolution of the influent quality, COD_{in} , (Figure 10), the evolution of the setpoint COD_{sp} and the controlled variable COD (Figure 11), as well as the evolution of the optimization criterion *J* (Figure 12).

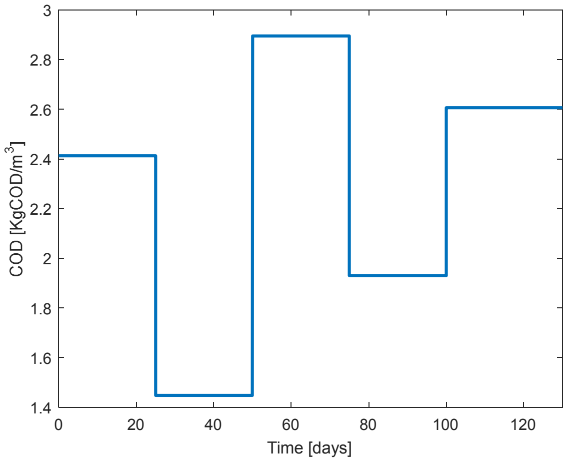

Fig. 10. Evolution of influent quality, COD_{in} .

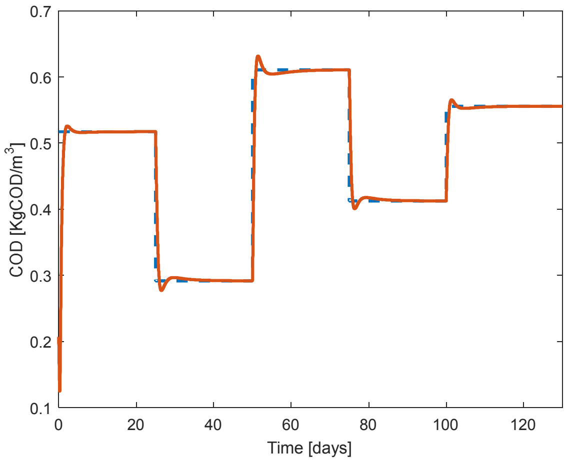

Fig. 11. Evolution of the COD_{sp} setpoint and the controlled variable COD (dotted blue – setpoint; continuous red – output variable).

V. Conclusions

The QFT linear robust control method gives very good results in the case of the anaerobic digestion process managing to incorporate aspects regarding the parametric uncertainties that affects this process and the aspects regarding the nonlinearity of the model. The resulted robust controller can be easily incorporated in a model-based optimization solution where the loop setpoint is computed from the characteristics of the optimal regimes obtained based on a mathematical model.

As future work we intend to consider the case when the information regarding the influent quality are not available and to complete our solution by adding a robust observer for the input concentration estimation.

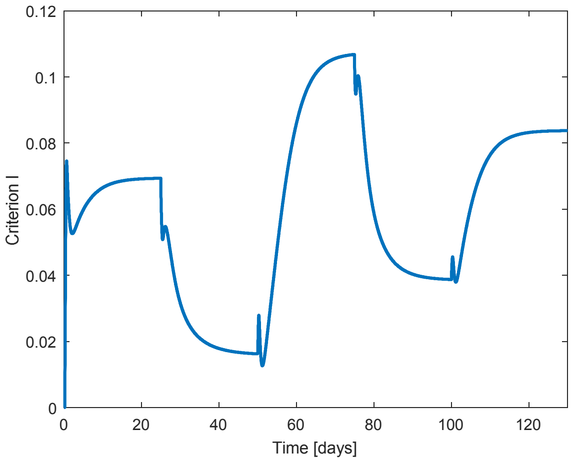

Fig. 12. Evolution of the optimization criterion *J*.

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REFERENCES

[1] M. Barbu, R. Vilanova, M. Meneses, I. Santin, "On the evaluation of the global impact of control strategies applied to wastewater treatment plants", J. Clean. Prod., Vol. 149, Pp. 396-405, 2017.

[2] I. Santin, M. Barbu, C. Pedret, R. Vilanova, "Control strategies for nitrous oxide emissions reduction on wastewater treatment plants operation", Water Res., Vol. 125, Pp. 466-477, 2017.

[3] M. Barbu, I. Santin, R. Vilanova, "Applying Control Actions for Water Line and Sludge Line To Increase Wastewater Treatment Plant Performance", Ind. Eng. Chem. Res., Vol. 57, Pp. 5630–5638, 2018.

[4] I. Santin, M. Barbu, C. Pedret, R. Vilanova, "Fuzzy logic for plant-wide control of biological wastewater treatment process including greenhouse gas emission", ISA Transactions, Vol. 77, Pp. 146-166, 2018.

[5] J.P. Steyer, O. Bernard, D.J. Batstone, I. Angelidaki, Lessons learnt from 15 years of ICA in anaerobic digesters. Water Sci Technol Vol. 53, Pp. 25–33, 2006.

[6] D. Batstone, J. Keller, I. Agelidaki, S. Kalyuzhnyi, S. Pavlostathis, A. Rozzi, W. Sanders, H. Siegrist, V. Vavilin, The IWA Anaerobic Digestion Model no. 1 (ADM1), IWA Publishing, 2002.

[7] O. Bernard, Z. Hadj-Sadok, A. Genovesi, J.P. Steyer, "Dynamical model development and parameter identification for an anaerobic wastewater treatment process", Biotechnology and Bioengineering, Vol. 75, Pp. 424-438, 2001.

[8] S. Hassam, E. Ficara, A. Leva, J. Harmand, "A generic and systematic pro-cedure to derive a simplified model from the Anaerobic Digestion Model No. 1(ADM1)", Biochem. Eng. J., Vol. 99, Pp. 193-203, 2015.

[9] G. Giovannini, M. Sbarciog, J.P. Steyer, R. Chamy, A.Vande Wouwer, "On the derivation of a simple dynamic model of anaerobic digestion including the evolution of hydrogen", Water Research, Vol. 134, Pp. 209-225, 2018.

[10] E. Petre, D. Selisteanu, D. Sendrescu, "Adaptive and robust-adaptive control strategies for anaerobic wastewater treatment bioprocesses", Chem. Eng. J., Vol. 217, Pp. 363–378, 2013.

[11] D. Dochain, M. Perrier, M. Guay, "Extremum seeking control and its application to process and reaction systems: a survey", Math Comput Simulat, Vol. 82, Pp. 369–380, 2011.

[12] M. Barbu, E. Ceangă, R. Vilanova, S. Caraman, G. Ifrim, "Extremum-Seeking Control Approach Based on the Influent Variability for Anaerobic Digestion Optimization", IFAC World Congress, Vol. 50, Pp. 12623-12628, 2017.

[13] J. Jimenez et al., "Instrumentation and control of anaerobic digestion processes: a review and some research challenges", Rev Environ Sci Biotechnol, Vol. 14, Pp. 615–648, 2015

[14] S. Caraman, M. Barbu, G. Ifrim, M. Titica, E. Ceangă, "Anaerobic Digester Optimization Using Extremum Seeking and Model-Based Algorithms. A Comparative Study", IFAC World Congress, Vol. 50, Pp. 12673–12678, 2017.

[15] I.M. Horowitz, "Optimum loop transfer function in single-loop minimum phase feedback systems", International Journal of Control, Vol. 22, Pp. 97-113, 1973.

[16] M. Barbu, G. Ifrim, S. Caraman, G. Bahrim, "QFT control of dissolved oxygen concentration in a wastewater treatment pilot plant", 11th IFAC International on Computer Applications in Biotechnology, Vol. 43, Pp. 233-238, 2010.

[17] M. Garcia-Sanz, C.H. Houpis, Wind Energy Systems: Control Engineering Design, CRC Press, Taylor & Francis, 2012.