QFT MULTIVARIABLE CONTROL OF A BIOLOGICAL WASTEWATER TREATMENT PROCESS USING ASM1 MODEL

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Abstract: This paper deals with the robust control of the wastewater treatment process, considered as a multivariable system, using QFT (Quantitative Feedback Theory) method. The wastewater treatment process is described by a simplified variant of ASM1 (Activated Sludge Model 1) model. Since the process is multivariable an analysis of the channel interaction, using RGA (Relative Gain Array) method, is done. According to this analysis two command channels can be emphasized. The process model was linearized in three functioning points (rain, normal and drought) and a robust controller, using QFT method, has been designed. The multivariable control structure was validated through numerical simulation in every regime, the results of the effluent quality being according to the limits imposed by the law.

Keywords: Wastewater treatment process, Quantitative Feedback Theory, Relative Gain Array

1. INTRODUCTION

A very important problem that mankind has to face is connected to the pollution eradication, empoverishment of water resources and the decay of the leaving conditions of other forms of life. Our society being more and more industrialized, needs new treatment methods of residual waters generated in large quantities. Consequently, automation must contribute more and more to the increasing of the efficiency of the wastewater treatment processes and to the insuring of water resources that correspond, qualitatively, to the preserving of the receiving waters.

In the wastewater treatment processes the biological component based on the active sludge is widely used. It consists in reducing the quantities of organic matter and solid materials floating in the water. The wastewater treatment process is a very complex biotechnological process, non-linear and characterized by strong uncertainties, due to the implication of microorganism populations, which develop in a polluted environment, with the purpose of removing the harmful substances. Obviously, all these facts lead to the conclusion that robust control methods are needed with the aim of ensuring the quality of the effluent resulted from the biological treatment in accordance with the legal norms. This paper deals now with the difficulties in modelling and control, generated by the complexity of the wastewater biological treatment processes as is presented below.

Process modelling: In 1983, International Water Association (IWA) has formed a working group destined to promote and facilitate the practical methods of designing and operating the biological treatment systems for wastewater systems. As a result of this work, the Activated Sludge Model 1 (ASM1) has been presented in 1987 (Henze *et al.*, 1987). The model used 13 state variables and it described the elimination of the organic carbon and nitrogen. The same working group extended the model afterwards by adding the biological process of eliminating the phosphorus, and named this model the Activated Sludge Model 2 (ASM 2) (Henze *et al.*, 1995). Two other improved versions of the ASM

2, named ASM2d and ASM3 appeared (Henze *et al.*, 2000). The major shortcoming of the ASM 1 is its complexity, which makes it difficult to be used in a control system. A simplified alternative of the ASM 1 model was obtained by taking into consideration the significant variables on a medium time-scale (a few hours to several days). This is why the variables with a slow evolution are considered constant and those having a fast evolution will be neglected (Jeppsson, 1996). These simplifications allowed the usage of ASM 1 model in designing control laws.

Process control: There are two types of approaches in choosing the control structure: one is process-driven and the other is oriented towards the mathematical model. The first approach deals with the separate control of the most important parameters. Within this category, the well-known problem of controlling the dissolved oxygen level is one of the most important issues for a good operation of the wastewater treatment plants. Thus, a good level of dissolved oxygen allows the optimal growth of microorganisms used in the process (Ingildsen, 2002). Recently, the control of nitrogen and phosphor level received also a lot of attention (Samuelsson, 2005). The second approach - the one based on the mathematical model - has been improved a number of times. These improvements depend on the type of the mathematical model, as in the case of state estimators. The use of the simplified models allowed the application of advanced control techniques (exact feedback linearization or adaptive control, robust control techniques etc.) (Nejjari *et al.*, 1999). When using the ASM1 model, the issue of automatic control becomes very complex and the results are not numerous. For the ASM 1 model the classical control techniques are usually used (PI, PID controllers), arranged hierarchically, in a three - level structure (Brdys and Zhang, 2001): at the higher level, a stable trajectory for the process is calculated for a certain time period; the medium level deals with the trajectory optimization for the dissolved oxygen, the flow of the recycled active sludge and the recycled inflow for nitrogen removal; at the lower level, the control of dissolved oxygen concentration is achieved, based on the medium level reference.

This paper aims to determine a multivariable robust controller for a wastewater treatment process and it is structured as follows: the second section contains a brief description of ASM1 model, the third section presents an analysis of the interaction between the wastewater treatment process channels based on RGA algorithm, the fourth section presents the QFT controller and prefilter design. It also contains the simulation results. The last section is dedicated to the conclusions.

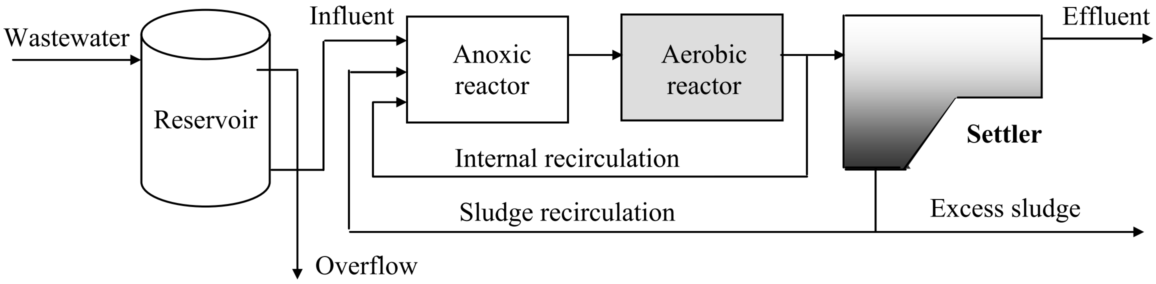

Figure 1: Wastewater treatment plant

2. SOME ASPECTS REGARDING THE MODELLING OF THE WASTEWATER TREATMENT PROCESS

In the paper a wastewater treatment plant with activated sludge aiming the removal of the organic carbon and nitrogen is considered. It contains three tanks, as it can be seen in Figure 1.

The plant is described by a simplified variant of ASM1 model. In this model only the significant variables on a medium scale of time are considered. Consequently, some processes with slow variations in time (the growth of autotrophic and heterotrophic microorganisms, the ammonification and hydrolyze processes) are neglected. In these conditions the model ASM1 is given by the following equations:

$$\frac{dS_{NH}(1)}{dt}=\frac{Q}{V_1}S_{NH,in}-\frac{Q+Q_i}{V_1}S_{NH}(1)+\frac{Q_i}{V_1}S_{NH}(2)-i_{XB}P_2(1) \quad (1)$$

$$\frac{dS_{NH}(2)}{dt}=\frac{Q+Q_i}{V_2}S_{NH}(1)-\frac{Q+Q_i}{V_2}S_{NH}(2)- -i_{XB}P_1(2)-\left(i_{XB}+\frac{1}{Y_A}\right)P_3(2) \quad (2)$$

$$\frac{dS_{NO}(1)}{dt}=-\frac{Q+Q_i}{V_1}S_{NO}(1)+\frac{Q_i}{V_1}S_{NO}(2)-\frac{1-Y_H}{2.86Y_H}P_2(1) \quad (3)$$

$$\frac{dS_{NO}(2)}{dt}=\frac{Q+Q_i}{V_2}S_{NO}(1)-\frac{Q+Q_i}{V_2}S_{NO}(2)+\frac{1}{Y_A}P_3(2) \quad (4)$$

$$\frac{dS_S(1)}{dt}=\frac{Q}{V_1}S_{S,in}-\frac{Q+Q_i}{V_1}S_S(1)+\frac{Q_i}{V_1}S_S(2)-\frac{1}{Y_H}P_2(1) \quad (5)$$

$$\frac{dS_S(2)}{dt} = \frac{Q+Q_i}{V_2} S_S(1) - \frac{Q+Q_i}{V_2} S_S(2) - \frac{1}{Y_H} P_1(2) \quad (6)$$

with

$$P_1(1) = \mu_H \frac{S_S(1)}{K_S + S_S(1)} \frac{S_O(1)}{K_{O,H} + S_O(1)} X_{B,H} \quad (7)$$

$$P_1(2) = \mu_H \frac{S_S(2)}{K_S + S_S(2)} \frac{S_O(2)}{K_{O,H} + S_O(2)} X_{B,H} \quad (8)$$

$$P_2(1) = \frac{\mu_H S_S(1)}{K_S + S_S(1)} \frac{K_{O,H}}{K_{O,H} + S_O(1)} \frac{S_{NO}(1) X_{B,H}}{K_{NO} + S_{NO}(1)} \eta_g \quad (9)$$

$$P_2(2) = \mu_H \frac{S_S(2)}{K_S + S_S(2)} \frac{K_{O,H}}{K_{O,H} + S_O(2)} \frac{S_{NO}(2) X_{B,H}}{K_{NO} + S_{NO}(2)} \eta_g \quad (10)$$

$$P_3(1) = \mu_A \frac{S_{NH}(1)}{K_{NH} + S_{NH}(1)} \frac{S_O(1)}{K_{O,A} + S_O(1)} X_{B,A} \quad (11)$$

$$P_3(2) = \mu_A \frac{S_{NH}(2)}{K_{NH} + S_{NH}(2)} \frac{S_O(2)}{K_{O,A} + S_O(2)} X_{B,A} \quad (12)$$

In equations (1) – (12) the following state variables are used: S_S – the soluble readily biodegradable substrate; S_{NO} – the soluble nitrate nitrogen and S_{NH} – the soluble ammonium nitrogen. The index 1 refers to the anoxic tank and index 2 refers to the aerated tank. The input variables are: the internal recycled flow, Q_i, the dissolved oxygen concentration from the aerated tank, $S_o(2)$, and the carbon external dosage, S_{s_dosage}. The output variables are the ammonium concentration at the output, $S_{NH}(2)$, equal to the ammonium concentration from the aerated tank and the nitrate concentration at the output, $S_{NO}(2)$, equal to the nitrate concentration from the aerated tank. The purpose of the control structure is the obtaining of an effluent having the ammonium concentration at the output under 1 gN/m^3 and the nitrate concentration at the output under 6 gN/m^3, both limits being imposed by the law.

3. THE RGA ANALYSIS OF THE PROCESS MODEL

3.1 RGA analysis method. Theoretical background

The most frequently used measure of the interactions for a MIMO linear system is RGA method, introduced by Bristol (Bristol, 1966) in 1966. A RGA square process is given by the equation:

$$RGA(G) = G(0).*\left(G(0)^{-1}\right)^T \quad (13)$$

where $G(0)$ is the transfer matrix in steady-state regime and „$.*$" represents the Schur product (the multiplication element by element). The RGA analysis method is independent by the input and output normalization.

The RGA method has been also generalized for nonsquare multivariable systems (Skogestad and Postlethwaite, 1996). In the case of these systems the analysis method has a supplementary purpose: the transformation of the nonsquare system in a square one through the elimination of the inputs/outputs with the smallest influence in the system. For a multivariable system, described by the transfer matrix *A* of $l \times m$ size, the RGA matrix is defined by equation (14):

$$\Lambda(A) = A \times (A^{\dagger})^T \quad (14)$$

where $A^{\dagger}$ is the pseudoinverse of the matrix *A*.

In the case of nonsquare systems, the RGA method has the following properties:

1. If the system is of line rank: $rang(A) = l$ (the input number is greater or at least equal to the output one and the outputs are linear – independent), than $AA^{\dagger} = I$ and the following two properties are true:
   a) The RGA method is independent of the input scaling, so that: $\Lambda(D \cdot A) = \Lambda(A)$;
   b) The sum of the elements from every line of RGA matrix is equal to 1, so that: $\sum_{j=1}^{m} \lambda_{ij} = 1$.

In the case of these systems, after the RGA matrix is determined, the column sum of RGA matrix is calculated and the $m - l$ inputs, which have the smallest sum of the columns, are removed. It results a square system of *l* order.

2. If the system is of column rank: $rang(A) = m$ (the output number is greater or at least equal to the input one and the inputs are linear – independent), than $AA^{\dagger} = I$ and the following two properties are true:
   c) The RGA method is independent of the input scaling, so that: $\Lambda(A \cdot D) = \Lambda(A)$;
   d) The sum of the elements from every column of RGA matrix is equal to 1, so that: $\sum_{i=1}^{l} \lambda_{ij} = 1$.

In the case of these systems, after the RGA matrix is determined, the line sum of RGA matrix is calculated and the $l - m$ outputs, which have the smallest sum of the lines, are removed. It results a square system of *m* order.

3.2 The RGA analysis of the wastewater treatment process

The non-linear wastewater treatment process can be linearized taking into consideration three main functioning points:

1. rain - $S_{NH,in}$=25 gN/m^3, $S_O(2) = 1$ mg/l, $S_{S,in}$=100+$S_{Sdosage}$ gCOD/m^3, $S_{Sdosage}$=50 gCOD/ m^3,

Q_i=30000 m^3/zi;

2. normal - $S_{NH,in}$=30 gN/m^3, $S_O(2) = 1.5$ mg/l, $S_{S,in}$=115+$S_{Sdosage}$ gCOD/m^3, $S_{Sdosage}$=50 gCOD/ m^3, Q_i=40000 m^3/zi;
3. drought - $S_{NH,in}$=35 gN/m^3, $S_O(2) = 2$ mg/l,, $S_{S,in}$=130+$S_{Sdosage}$ gCOD/m^3, $S_{Sdosage}$=50 gCOD/ m^3 Q_i=50000 m^3/zi.

The linear multivariable model, obtained through linearization, is described by the equation (15). It can be seen that the matrix of the transfer functions is nonsquare, therefore the RGA method for the nonsquared systems must be used.

$$\begin{bmatrix} NH(2) \\ NO(2) \end{bmatrix} = \begin{bmatrix} G_{S_O(2)-NH(2)} & G_{Q_i-NH(2)} & G_{S_{Sdozaj}-NH(2)} \\ G_{S_O(2)-NO(2)} & G_{Q_i-NO(2)} & G_{S_{Sdozaj}-NO(2)} \end{bmatrix} \begin{bmatrix} S_O(2) \\ Q_i \\ S_{Sdozaj} \end{bmatrix} \tag{15}$$

For example, the *rain* regime is described by the following transfer functions:

$$G_{S_O(2)-NH(2)}(s) = \frac{-24.63s^5 - 6223s^4 - 4.095\cdot10^7 s^3 - 2.318\cdot10^9 s^2 - 4.365\cdot10^{10} s - 2.575\cdot10^{11}}{s^6 + 2711s^5 + 2.048\cdot10^6 s^4 + 2.89\cdot10^8 s^3 + 1.231\cdot10^{10} s^2 + 2.026\cdot10^{11} s + 1.11\cdot10^{12}} \tag{16}$$

$$G_{Q_i-NH(2)}(s) = \frac{0.001861s^5 + 4.564s^4 + 2832s^3 + 9736s^2 + 76070s - 1204}{s^6 + 2711s^5 + 2.048\cdot10^6 s^4 + 2.89\cdot10^8 s^3 + 1.231\cdot10^{10} s^2 + 2.026\cdot10^{11} s + 1.11\cdot10^{12}} \tag{17}$$

$$G_{S_{Sdozaj}-NH(2)}(s) = \frac{-7377s^3 - 9.844\cdot10^6 s^2 - 3.488\cdot10^8 s - 2.748\cdot10^9}{s^6 + 2711s^5 + 2.048\cdot10^6 s^4 + 2.89\cdot10^8 s^3 + 1.231\cdot10^{10} s^2 + 2.026\cdot10^{11} s + 1.11\cdot10^{12}} \tag{18}$$

$$G_{S_O(2)-NO(2)}(s) = \frac{22.62s^5 + 5875s^4 + 3.982\cdot10^7 s^3 2.251\cdot10^9 s^2 + 3.6\cdot10^{10} s + 9.776\cdot10^{10}}{s^6 + 2711s^5 + 2.048\cdot10^6 s^4 + 2.89\cdot10^8 s^3 + 1.231\cdot10^{10} s^2 + 2.026\cdot10^{11} s + 1.11\cdot10^{12}} \tag{19}$$

$$G_{Q_i-NO(2)}(s) = \frac{-0.001634s^5 - 4.197s^4 - 2815s^3 - 16520s^2 - 8.519\cdot10^6 s - 1.47\cdot10^8}{s^6 + 2711s^5 + 2.048\cdot10^6 s^4 + 2.89\cdot10^8 s^3 + 1.231\cdot10^{10} s^2 + 2.026\cdot10^{11} s + 1.11\cdot10^{12}} \tag{20}$$

$$G_{S_{Sdozaj}-NO(2)}(s) = \frac{-298.3s^3 - 1.089\cdot10^6 s^2 - 9.554\cdot10^8 s - 2.244\cdot10^{10}}{s^6 + 2711s^5 + 2.048\cdot10^6 s^4 + 2.89\cdot10^8 s^3 + 1.231\cdot10^{10} s^2 + 2.026\cdot10^{11} s + 1.11\cdot10^{12}} \tag{21}$$

It results the following matrix of the static transfer coefficients:

$$G(0) = \begin{bmatrix} -0.232 & -1.084\cdot10^{-9} & -0.0025 \\ 0.088 & -0.00013 & -0.02 \end{bmatrix} \tag{22}$$

Let us consider as scaling matrix the diagonal matrix of input values:

$$D_u = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 30000 & 0 \\ 0 & 0 & 30 \end{bmatrix} \tag{23}$$

The RGA matrix is obtained

$$\Lambda_1 = \begin{bmatrix} 0.9082 & -0.0000 & 0.0918 \\ 0.0010 & 0.9774 & 0.0216 \end{bmatrix} \tag{24}$$

Making the sum on the columns, it can be noticed that the smallest value is given by the column 3, therefore the command variable with the smallest influence in the system is the external carbon dosage S_{Sdozaj}. Taking into account the values $\lambda_{11} = 0.9082$ and $\lambda_{22} = 0.9774$, very close to the value 1, it results the following command channels: the dissolved oxygen concentration from the aerated tank – the ammonium concentration at the output ($S_O(2) - NH(2)$) and the recycle rate – the nitrate concentration at the output (Q_i - $NO(2)$). At the same time, as $\lambda_{12} \approx 0$ and $\lambda_{21} = 0.0010$, are values very close to 0, it results a very weak interaction between the other two channels: the recycle rate – the nitrate concentration at the output (Q_i - $NH(2)$) and the dissolved oxygen concentration from the aerated tank – the nitrate concentration at the output ($S_O(2) - NO(2)$).

The RGA matrices for the other two functioning regimes are calculated in the same way:

$$\Lambda_2 = \begin{bmatrix} 0.844 & -0.053 & 0.209 \\ 0.047 & 0.937 & 0.016 \end{bmatrix} \tag{25}$$

$$\Lambda_3 = \begin{bmatrix} 1.032 & -0.243 & 0.211 \\ -0.144 & 1.13 & 0.014 \end{bmatrix} \tag{26}$$

They reach similar results.

In these conditions, the input variable – the external carbon dosage – will be considered as a parameter of the model, having a constant value. At the same time, the RGA analysis indicates the fact that a control structure based on decentralized loops, considering as main channels – the command channels and as secondary channels – the disturbance channels, could be adopted. The transfer functions obtained in the case of the three functioning regimes were simplified through frequency analysis and they have the following expressions:

1. Rain

$$P_{S_O(2)-NH(2)}(s)=\frac{-23.664}{s+115} \quad (27)$$

$$P_{Q_i-NH(2)}(s)=\frac{0.00158(s-0.01622)}{(s+115)(s+22.56)} \quad (28)$$

$$P_{S_O(2)-NO(2)}(s)=\frac{21.085(s+3.392)(s+32.95)}{(s+115)(s+11.82)(s+22.56)} \quad (29)$$

$$P_{Q_i-NO(2)}(s)=\frac{-0.00149(s^2+36.03s+2596)}{(s+115)(s+11.82)(s+22.56)} \quad (30)$$

2. Normal

$$P_{S_O(2)-NH(2)}(s)=\frac{-15.036}{s+115.4} \quad (31)$$

$$P_{Q_i-NH(2)}(s)=\frac{0.00168(s-0.01493)}{(s+115.4)(s+26.92)} \quad (32)$$

$$P_{S_O(2)-NO(2)}(s)=\frac{13.136(s+40.51)(s+3.33)}{(s+115.4)(s+13.75)(s+26.92)} \quad (33)$$

$$P_{Q_i-NO(2)}(s)=\frac{-0.00156(s^2+41.81s+2924)}{(s+115.4)(s+13.75)(s+26.92)} \quad (34)$$

3. Drought

$$P_{S_O(2)-NH(2)}(s)=\frac{-11.32}{s+109.6} \quad (35)$$

$$P_{Q_i-NH(2)}(s)=\frac{0.00168(s-0.01359)}{(s+109.6)(s+29.13)} \quad (36)$$

$$P_{S_O(2)-NO(2)}(s)=\frac{8.6175(s+48.05)(s+3.291)}{(s+109.6)(s+13.68)(s+29.13)} \quad (37)$$

$$P_{Q_i-NO(2)}(s)=\frac{-0.00149(s^2+42.66s+2584)}{(s+109.6)(s+13.68)(s+29.13)} \quad (38)$$

4. THE QFT CONTROL OF THE WASTEWATER TREATMENT PROCESS

Taking into account the transfer functions obtained for the three functioning regimes, it can be seen that the main channel, the dissolved oxygen concentration from the aerated tank – the ammonium concentration at the output ($S_O(2)-NH(2)$) can be described by the following transfer function with variable parameters:

$$P_{S_O(2)-NH(2)}(s)=\frac{K_1}{s+a_1} \quad (39)$$

where: $K_1 \in [10\ \ 20],\ a_1 \in [109\ \ 116]$.

All the design steps of QFT algorithm were taken using the QFT Matlab® toolbox. It has been obtained the controller:

$$G_{S_O(2)-NH(2)}(s)=\frac{270.2621}{s+0.063} \quad (40)$$

and the prefilter:

$$F_{S_O(2)-NH(2)}(s)=\frac{45.205}{s+45.205} \quad (41)$$

The command channel, the recycled rate – the nitrate concentration at the output (Q_i - $NO(2)$), is described by the following transfer function with variable parameters:

$$P_{Q_i-NO(2)}(s)=\frac{K_2(s^2+a_2s+b_2)}{(s+c_2)(s+d_2)(s+e_2)} \quad (42)$$

with:
$K_2 \in [0.0014\ 0.0016],\ a_2 \in [36\ 43],\ b_2 \in [2580\ 930],$
$c_2 \in [109\ 116],\ d_2 \in [11.5\ 14],\ e_2 \in [22\ 29.5]$

As a result of applying the QFT algorithm, the following robust controller results:

$$G_{Q_i-NO(2)}(s)=\frac{10000(0.965s+13.255)}{s+0.0067} \quad (43)$$

and the prefilter:

$$F_{Q_i-NO(2)}(s)=\frac{1.07s+25.194}{s+25.194} \quad (44)$$

The robust control structure proposed in this paper has been tested by numerical simulation in the case of each of the three functioning regimes. Because of the lack of space, the paper only presents the simulation results in the case of "rain" regime – Figure 2. It was also tested a functioning sequence when the three functioning regimes alternate, as is presented in Figure 3. Both figures show that the robust multivariable control structure is able to track the setpoints imposed for the output variables and the biodegradable substrate is efficiently treated.

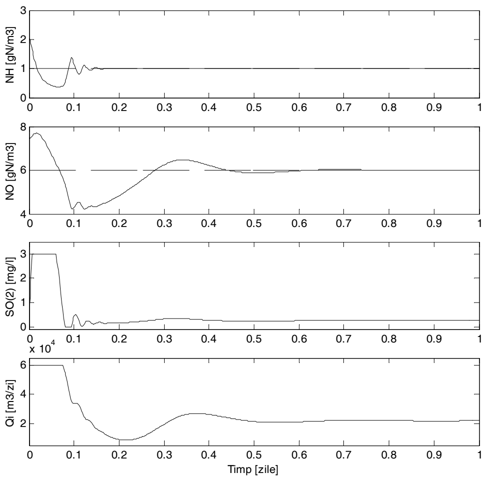

Fig. 2: QFT robust control applied in the case of "rain" regime

5. CONCLUSIONS

In the implementing of the control structures for the wastewater treatment processes the starting point was the classic models existing in the literature (ASM1 model). The models used in the present paper are multivariable and they need a first phase of quantitative evaluation of the existing input/output influences. This is done by means of RGA analysis. According to this analysis, it became obviously that the multivariable control by decentralized loops can be used. Consequently, the QFT robust control algorithm has been applied for the main command channels, the results being very good. In all the three functioning regimes (rain, normal and drought) the contents of polluting substances is under the limit imposed by law. Further on, the authors intend to validate the results obtained in the paper on a pilot plant and on the Benchmark Simulation Model No. 1 (BSM 1).

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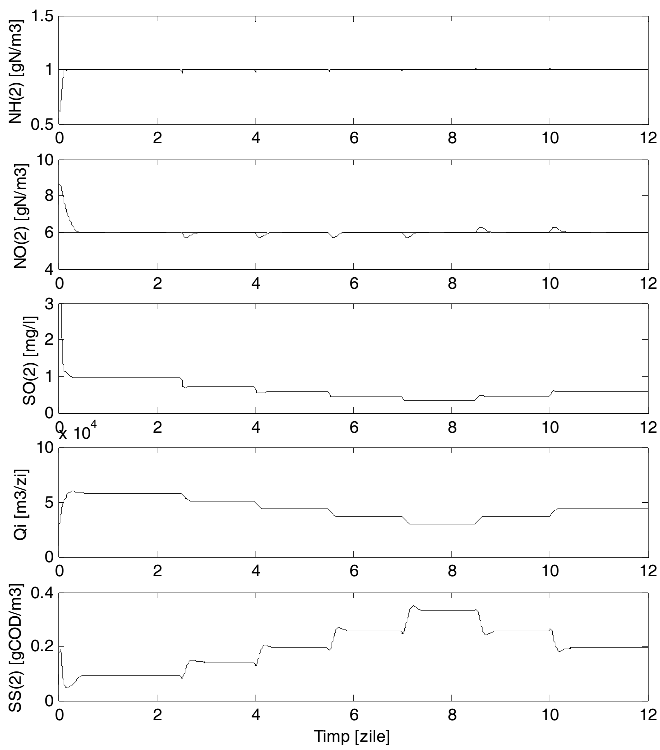

Fig. 3: QFT robust control of the wastewater treatment process (variable setpoint)