Deriving rules of thumb for the control of a novel WWTP using a dynamical model

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Abstraction

Traditional wastewater treatment technologies, which are based on activated sludge systems, have been used to meet the discharge guidelines outlined by the authorities. However, these systems use huge amounts of energy, which in addition to the conversion of organic matter to CO_2 and require extra process steps to meet the increasingly stringent wastewater discharge guidelines.

The development of new technological methods should aim for higher removal efficiency and nutrients recovery, improving the energy production and reducing the costs.

In this study, existing and novel processes which consists of bioflocculation as a pre-treatment step, and anaerobic sludge digestion for energy (biogas) production are integrated. Partial nitritation and Anammox processes are used for the nitrogen removal and a novel phosphorus treatment step is introduced to recover the phosphate in the wastewater.

In a previous study by Elvira Bozileva (2013), dynamical model which focusses exclusively on the processes that are involved in the removal of COD and nitrogen and the production of biogas has been developed to research and identify the optimal operational condition. However, this model acquire intensive simulation to find the optimal condition of each of this processes because of its complexity.

The main goal of this work is to develop a simple model with wide applicability and which is easy to use in practice, starting from the dynamical model. The simple model consist of a number of algebraic functions which replace the differential equations of the dynamical model.

As first step, the functions that relate for the sludge retention time (SRT) and oxygen transfer coefficient (KOLa) is developed for instance, for the bioflocculation (BF) and partial nitritation (PN) processes. The function relate SRT to KOLa for specific COD concentration and temperatures levels and for condition under which 65% of the concentrated COD is converted into methane for the bioflocculation. For the partial nitritation process, the functions provide the relationship between SRT and KOLa for specific COD and N concentrations under which ensures that the effluent quality will meet the new discharge levels.

The drawback of these functions is that they provide less accurate SRT and KOLa values and it is exclusively valid for certain operational condition. Additionally, the effect of the change in the KOLa of the BF process on the performance of the PN process need to be evaluated, as the SRT and KOLa values in the PN process could be influenced by the change of the KOLa in the BF process. Nevertheless, these functions replace the differential equations and reduce the simulation time. These functions could be used to describe the control inputs of the anaerobic digester and Anammox processes.

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Introduction

Conventional wastewater treatment technologies, which are based on activated sludge systems, have been used for the removal of organic materials, nitrogen and phosphorous to meet the discharge guidelines outlined by the authorities. However, huge amounts of energy are generally used for aeration, which in addition to the conversion of organic matter to CO_2. Additionally, valuable nutrients such as phosphorous are lost in the activated sludge systems. Another drawback is that conventional wastewater treatment technologies require extra process steps to meet the increasingly stringent wastewater discharge guidelines [1]. Therefore, the development of new technological methods should aim for higher removal efficiency and nutrients recovery, improving the energy production and reducing of the costs.

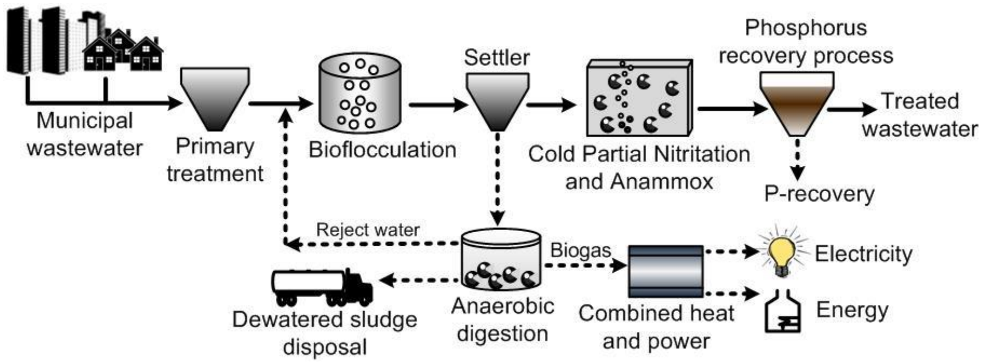

Figure 1. Wastewater treatment scenario proposed by Khiewwijit, 2013 (in preparation)

A novel concept has been introduced by Khiewwijit, 2013 (in preparation) where several scenarios have been proposed for the municipal wastewater treatment plants (WWTP) in the Netherlands (Figure 1). This concept aims at improving the potential energy and nutrients recovery and the reduction of CO2, while meeting the effluent standard is considered. In this concept, existing and novel processes are integrated which consists of bioflocculation (BF) as a pre-treatment step, and anaerobic sludge digestion (AD) for energy (biogas) production. The bioflocculation process provides flocculated organic matter with high COD concentration for the anaerobic digester. In the BF process, aerobic micro-organisms produce extracellular polymers by using a small fraction of the soluble organic matter. These extracellular polymers function as flocculants for the suspended, colloidal and soluble COD [2, 3].

The concentrated and flocculated organic matter (sludge) is converted into energy such as biogas [4]. Subsequently, the effluent of the bioflocculation process which is rich of nutrients nitrogen and phosphorous are further treated to fulfill the discharge criteria. Cold partial nitritation (PN) and Anammox (ANA) processes are used for the nitrogen removal and a novel phosphorus treatment step is introduced to recover the phosphate in the wastewater [5].

A dynamical model of these processes has been developed to research and identify the optimal operational condition of the WWTP scenario in The Netherlands [6]. The dynamical model focusses exclusively on the processes that are involved in the removal of COD and nitrogen and the production of biogas. (Figure 2).

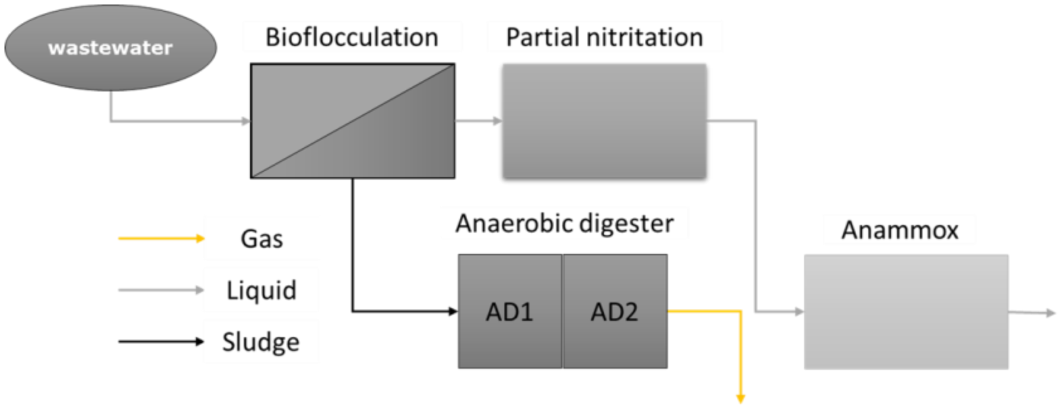

Figure 2. Units described in the dynamical model [5]

The dynamical model describes the microbial interactions and the physiochemical reactions of these processes in detail. The dynamical model consist of a number of differential equations which describe the mass balances for the species relevant to each process. However, this model acquire intensive simulation to find the optimal condition of each of this processes because of its complexity. In this work, the main goal is to evaluate, through dynamic simulation and response surface analysis, the WWTP scenarios and to derive rules of thumb for control implementation in practice.

In this work, we aim for a simple model with wide applicability and which is easy to use in practice, starting from the dynamical model. In principle, this simple model replace the differential equations of the dynamical model by algebraic equations, which describe exclusively the optimal operational conditions. The simple model consist of a number of functions, which relate several control inputs of a certain process at the optimal operational conditions and at specific disturbances levels. The final relationship also describe the effect of different disturbances levels on the control inputs at the optimal operational conditions. Finally, this model which in fact describe static, non-linear control laws, has been inserted into the dynamical model for evaluation.

The control inputs have an effect on the performance of the processes, for example the energy production and the nutrients removal. Energy production and the nutrients removal are both taken into account in the major objective of the concept. Both the optimal efficiency of methane production which is related to the level of the concentrated COD converted into methane, and the N removal have been selected as criteria for the operational conditions. The methane production efficiency is regulated by the BF and AD processes while the BF, PN and ANA processes are involved in the COD and N removal. In a first step, we focus on the relationship between the control inputs, the sludge retention time (SRT) and the oxygen transfer coefficient KOLa of the BF and PN processes. Hence, the research objectives are as follows:

- Identify the methane production efficiency as function of the BF process prior anaerobic digester and find the maximal dischargeable N concentration.
- Define the maximal dischargeable N concentration as function of the PN process.
- Evaluate the MBR and CSRT systems, for PN process and select the most efficient process configuration.
- Develop the algebraic functions between control inputs and disturbances for the BF and PN processes.
- Evaluate the developed model by inserting into the dynamical model.

Methodology

In this section, the strategy used to establish the control functions from the optimal operational conditions using the dynamical model is explained in detail.

Disturbances and control inputs

The influent total COD, N concentrations and temperature were selected as disturbance inputs (Table 1). The selected disturbances were varied in a specific range, which is typical for the influent of the municipal wastewater treatment plants [7].

Table 1. Influent characteristics of the wastewater as disturbances.

Disturbances	range	units
Organic matter (COD)	400-700	*Kg COD/m^3*
Nitrogen (N)	40-70	*Kg N/m^3*
Temperature (T)	15-30	$^\circ C$

The sludge retention time (SRT) [d] and the overall mass transfer coefficient for oxygen (KOLa) [d^{-1}] in the bioflocculation and partial nitritation units were chosen as the control inputs. For these control inputs static, nonlinear control laws were derived from simulations with the dynamic model. The SRT [d] of the bioflocculation and the partial nitritation units, at different disturbances was expressed as function of KOLa.

Simulation blocks for the development of the functions

The development of the functions was divided in two blocks, where in block I, the focus is on the optimal production of methane efficiency was focused and in the block II the effluent N concentrations (Figure 3). The relevant control inputs and disturbances were selected for each block.

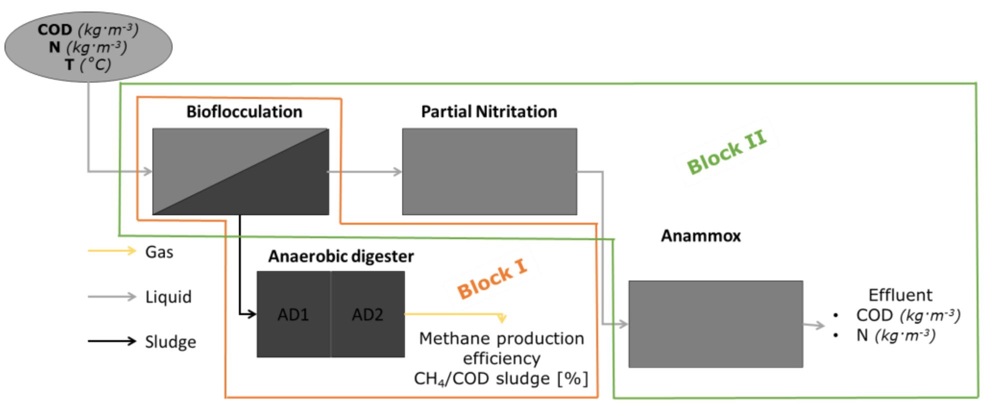

Figure 3. Simulation blocks for the development of the functions

As mentioned before, the dynamical model was used as a starting point and tool to establish the functions. Simulation of this model for the establishment of the functions was dynamic. For the derivation of the functions steady state conditions were selected, as a results of the constant disturbance input levels of COD, N and T, and was performed in a MATLAB software environment.

Functions

Methane production efficiency block

In the methane production efficiency block (I), the bioflocculation and anaerobic digester units were involved. In this block, different influent COD and temperature levels were used as disturbances (***see Appendix A***).

Through simulation of the dynamical model, the relations of SRT and KOLa of the bioflocculation was obtained for a specific methane production efficiency. This relation was described by a quadratic equation

$$SRT = a \cdot KOLa^2 + b \cdot KOLa + c \qquad \text{eq(1)}$$

Where a, b and c are the coefficients of the function of SRT and KOLa of the bioflocculation process for a certain COD concentration and temperature. Subsequently, functions that link the coefficients a_n, b_n and c_n with the disturbances (T and COD) was established. These functions were expressed as follows:

$$[a \quad b \quad c] = [1 \quad T \quad COD \quad T^2 \quad COD^2 \quad T * COD\,] \cdot \begin{bmatrix} \alpha_0 & \beta_0 & \gamma_0 \\ \alpha_1 & \beta_1 & \gamma_1 \\ \alpha_2 & \beta_2 & \gamma_2 \\ \alpha_3 & \beta_3 & \gamma_3 \\ \alpha_4 & \beta_4 & \gamma_4 \\ \alpha_5 & \beta_5 & \gamma_5 \end{bmatrix} \qquad \text{eq(2)}$$

and in matrix formation for linear regression as follows:

$$\begin{bmatrix} a_1 & b_1 & c_1 \\ a_2 & b_2 & c_2 \\ a_3 & b_3 & c_3 \\ a_4 & b_4 & c_4 \\ a_5 & b_5 & c_5 \\ a_6 & b_6 & c_6 \\ a_n & b_n & c_n \end{bmatrix} = \begin{bmatrix} 1 & T_1 & COD_1 & {T_1}^2 & {COD_1}^2 & T_1 \cdot COD_1 \\ 1 & T_2 & COD_2 & {T_2}^2 & {COD_2}^2 & T_2 \cdot COD_2 \\ 1 & T_3 & COD_3 & {T_3}^2 & {COD_3}^2 & T_3 \cdot COD_3 \\ 1 & T_4 & COD_4 & {T_4}^2 & {COD_4}^2 & T_4 \cdot COD_4 \\ 1 & T_5 & COD_5 & {T_5}^2 & {COD_5}^2 & T_5 \cdot COD_5 \\ 1 & T_6 & COD_6 & {T_6}^2 & {COD_6}^2 & T_6 \cdot COD_6 \\ 1 & T_n & COD_n & {T_n}^2 & {COD_n}^2 & T_n \cdot COD_n \end{bmatrix} \cdot \begin{bmatrix} \alpha_0 & \beta_0 & \gamma_0 \\ \alpha_1 & \beta_1 & \gamma_1 \\ \alpha_2 & \beta_2 & \gamma_2 \\ \alpha_3 & \beta_3 & \gamma_3 \\ \alpha_4 & \beta_4 & \gamma_4 \\ \alpha_5 & \beta_5 & \gamma_5 \end{bmatrix} \qquad \text{eq(3)}$$

Where α_m, β_m and γ_m are the constants of a polynomial second order function.

N removal block

In the block (II), the units, bioflocculation, partial nitritation and Anammox were relevant for establishment of the control functions. First, the partial nitritation unit was configured as a CSTR and MBR where the most robust system was selected for the partial nitritation. Subsequently, the optimal value for the SRT and KOLa of the bioflocculation was identified before the simulation of this block. In the N removal block, different influent COD and N concentration were used as disturbances (***see Appendix A***). The relation between SRT and KOLa of partial nitritation, at a specific nitrogen removal efficiency was described. This relationship was also described by a hyperbolic equation.

$$SRT = \frac{u}{KOLs} \qquad \text{eq(4)}$$

Subsequently, a similar procedure as for the methane block was used for the establishment of the control functions in the N removal block.

Results

First, we start to present the results of the methane production efficiency block, followed by the assumption and results of the N removal Block. Finally, the results are evaluated in a dynamical simulation.

Block I

Bioflocculation of municipal wastewater improves the methane production efficiency by providing concentrated COD to the anaerobic digester [2, 4]. Bioflocculation of municipal wastewater is still in the lab scale phase and almost no Literature information are available of this process. However, the BF process prior anaerobic digester in lab scale have reached an optimal methane production efficiency approximately 65% [4]. The methane production efficiency of the anaerobic digester is influenced by the control inputs of the BF process. Trough simulation of the dynamical, the relationships between the SRT and KOLa at different methane production efficiency are obtained (Figure 4).

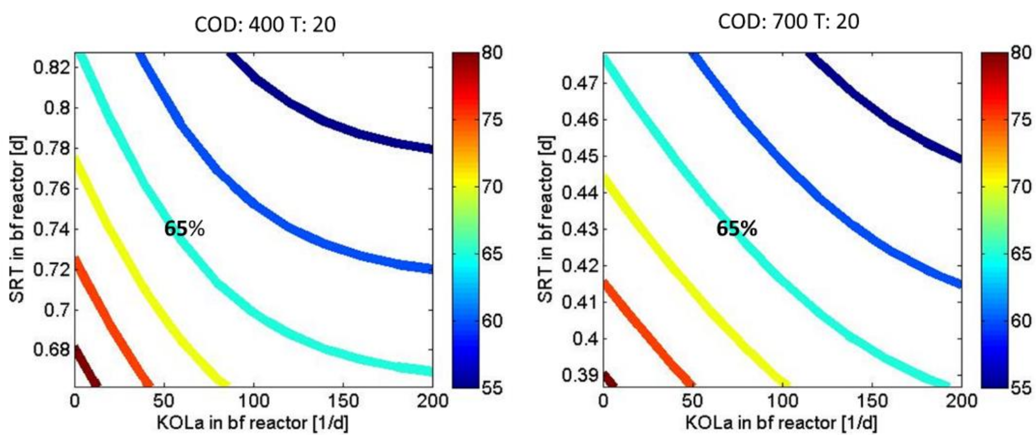

Figure 4. The relationship between the SRT and KOLa at different methane production efficiency in a contour plot

In this work, we focus on the relationship between SRT and KOLa of specific COD concentration and temperatures levels and at methane production efficiency of 65%. The results of the relation of SRT and KOLa are shown in Figure 5.

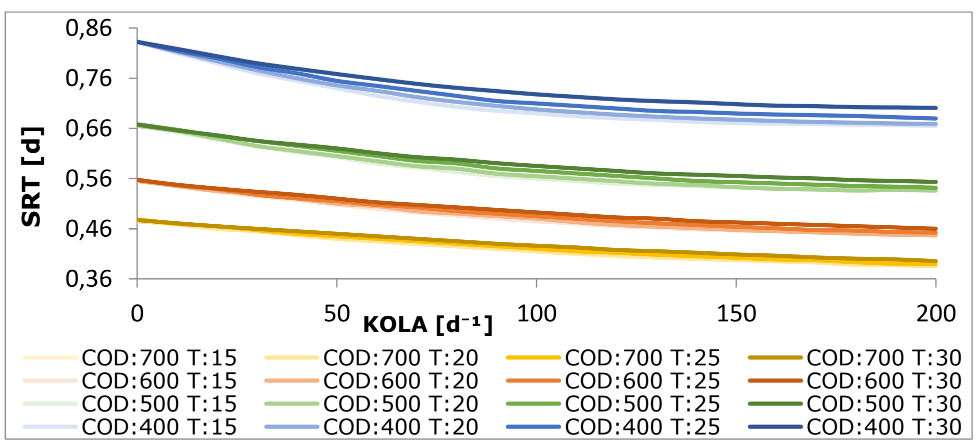

Figure 5. The relation of SRT and KOLa of different disturbances levels (T and COD) at methane production efficiency of 65%.

Figure 5 gives the relation of SRT and KOLa of specific COD concentrations and temperatures at methane production efficiency of 65%. Figure 5 shows that changing the temperature has no effect on the SRT and KOLa relationships of the BF process. The relation of SRT and KOLa is influenced exclusively by the COD levels. The results also indicate that the SRT should be decreased when COD concentrations increase to maintain the methane production efficiency at 65%.

The SRT decreases at the increase of the KOLa. However, the change of SRT over the KOLa range between 0 and 200 d^{-1} is very small. This indicates that the process is robust against the change in KOLa. Also, a wider KOLa range is favorable and could be safer, since the KOLa cannot be measured directly and therefore needed to be estimated from a model with the KOLa is as function of gas flow and even in some cases temperature [7, 8].

Each of the lines in represent the relation of SRT and KOLa at a specific disturbances levels. The function of each of these lines is defined by eq(1). The coefficients of these equations, namely a, b, and c, determine the relationships between the control inputs for the selected temperature and COD levels (Table 2).

Table 2. The coefficients of the function of SRT and KOLa of the bioflocculation process at a specific disturbances levels

T	COD	a	b	c
15	400	6,00E-06	2,00E-03	0,83
15	500	4,00E-06	1,50E-03	0,67
15	600	3,00E-06	1,10E-03	0,56
15	700	2,00E-06	8,00E-04	0,48
20	400	5,00E-06	1,80E-03	0,83
20	500	4,00E-06	1,40E-03	0,66
20	600	2,00E-06	1,00E-03	0,56
20	700	2,00E-06	8,00E-04	0,48
25	400	5,00E-06	1,80E-03	0,83
25	500	3,00E-06	1,20E-03	0,67
25	600	2,00E-06	9,00E-04	0,56
25	700	1,00E-06	7,00E-04	0,48
30	400	4,00E-06	1,40E-03	0,83
30	500	3,00E-06	1,10E-03	0,67
30	600	2,00E-06	8,00E-04	0,56
30	700	1,00E-06	6,00E-04	0,48

These coefficients and their corresponding disturbances levels are described with a polynomial second order function (eq 2 and 3). The constants of this function are given in Table 3.

Table 3. The constants of the function that link the coefficients a, b and c and the disturbances levels.

Constants	0	1	2	3	4	5
α	1,98 ±0.31**	-275 ±156 ***	-35.5 ±9.2 ***	2,50 ±1.2 ***	0.0188 ±0.01 ***	0.14 ±0.1***
β	5,8 ±0.53 *	-3,15 ±2.6 **	-1,13 ±0.15 **	-750 ±526 ***	5,63 ±1.31 ***	74.0 ±21***
γ	1,86 ±0.53	1.11 ±0.91 *	3.46 ±0.09 *	-0.850 ±0.34 **	0.21 ±0.08 **	-0.11 ±0.01**

***: $\cdot 10^{-3}$**
****: $\cdot 10^{-5}$**
*****: $\cdot 10^{-9}$**

The coefficients of the SRT and KOLa functions are calculated over the entire disturbance range with the constants of the polynomial second order function. The estimated coefficients a’, b’ and c’ and the obtained coefficients a, b and c from simulation of the dynamical model at different disturbances levels are shown in Figure 6 and 7.

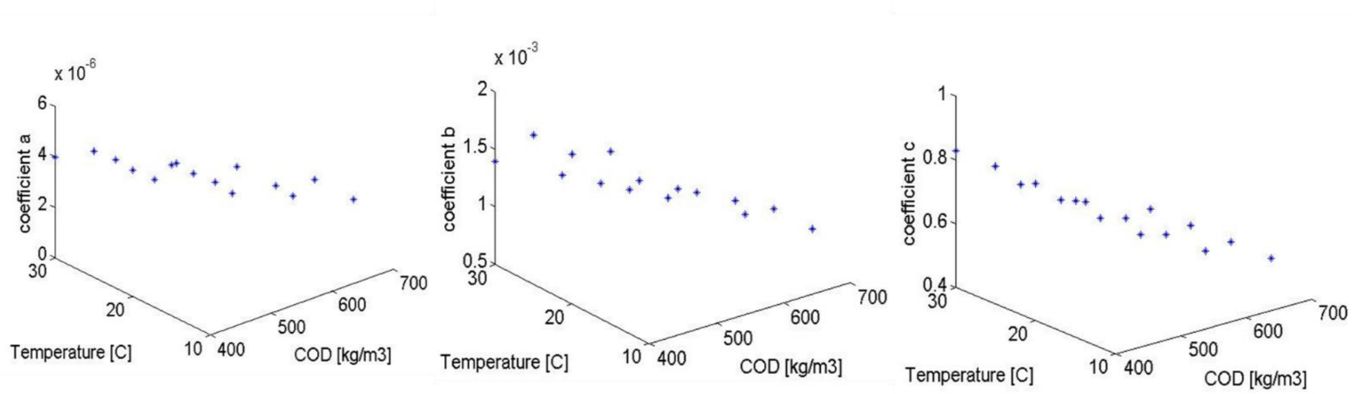

Figure 6. The coefficients a, b and c as function of COD concentration and temperature.

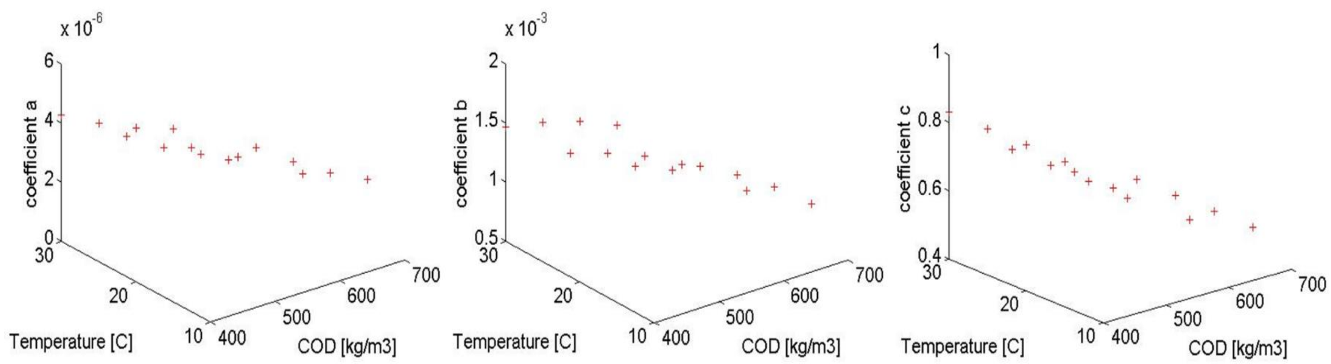

Figure 7. The estimated coefficients a’, b’ and c’ as function of COD concentration and temperature.

Figure 6 and 7 show both the coefficients a, b and c; and the estimated coefficients a’, b’ and c’; as a function of the disturbances (T and COD). The coefficients a’, b’ and c’ calculated with the polynomial second order function fit the coefficients a, b and c as a function of the disturbances (T and COD). This means that after substitution of eq (2) in eq (1), the relationship between the SRT and KOLa can be described in terms of the disturbance inputs (COD and T).

As mentioned before, the change of the influent COD concentration has influence on the methane production efficiency of the BF process prior to the anaerobic digester. The methane production efficiency is maintained at 65% for different COD levels by regulating particularly the SRT. The change of temperature levels and KOLA has almost no effect on the SRT. Little is known about the effect of the temperature, the KOLa and the microorganism activities on the process performance, since the literature information available of this process is limited.

Block II

Partial nitritation followed by an Anammox process is used to remove nitrogen at the levels of discharge guidelines. The maximal N concentration that is allowed to discharge is 10 $kg \cdot m^{-3}$. However, these values will change in the near future, especially for the nitrogen, as the legislation regulating the effluent concentration will be become more stringent due to the stress on the environment. The maximal effluent N concentration is expected to become 2.2 $kg \cdot m^{-3}$ [1].

Partial nitritation and Anammox process is carry out in a two-step reactor such as SHARON-Anammox. The SHARON process has no retention and as a result large reactors are needed to treat large flows [5]. The reactor size could be reduced by retaining the sludge using an MBR system. In an MBR system microorganisms are not washed out and recirculated. This could improve the performance of the process. Figure 8 shows the control inputs ranges of the CSTR and MBR system that can be operated to reach the required effluent N levels.

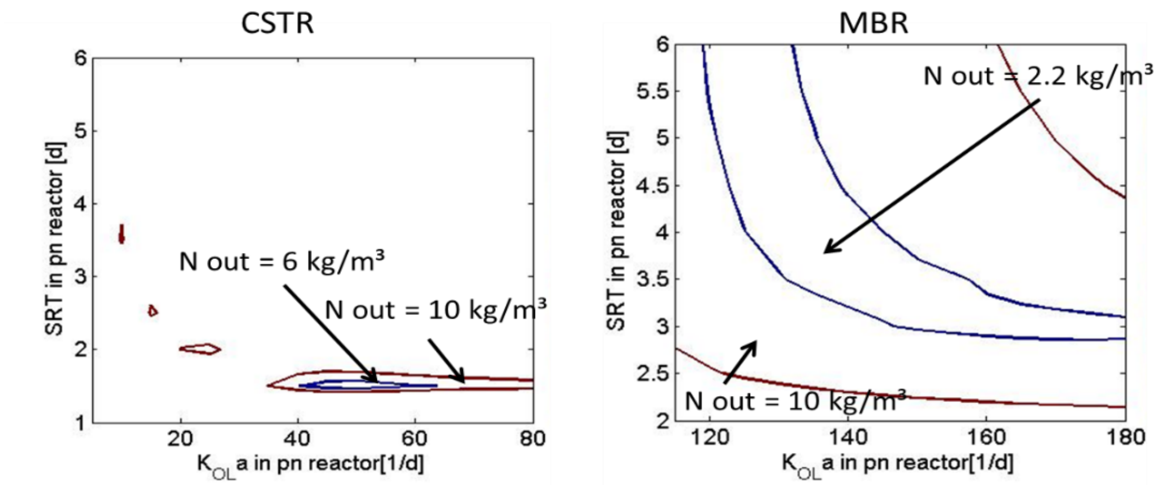

Figure 8. The SRT and KOLa levels of the CSTR and MBR system to meet the required effluent N concentration.

The SRT and KOLa ranges of the CSTR that provide the required effluent N levels are very narrow. The MBR system allow a wider SRT and KOLa ranges at the required effluent N levels compare to the CSTR system. Operating in a wider SRT and KOLa range makes the process more robust and more reliable implement in practice.

Partial nitritation plays an important role in the performance of the Anammox. Maintaining the optimal ammonium and nitrite ratio by retaining the ammonia oxidising bacteria (AOB) and preventing the production of nitrate by suppressing the nitrite oxidising bacteria (NOB) is crucial to reach the required effluent N levels [10]. This can be done by adjusting the SRT and KOLa. For this reason, we focus on the values of SRT and KOLa of the PN process which ensure that the effluent quality will meet the new discharge levels. The SRT and KOLa is influenced by the disturbances (COD, N and T). In figure 9, the effect of the temperature on the relationship between SRT and KOLa at the required N effluent N concentration is presented.

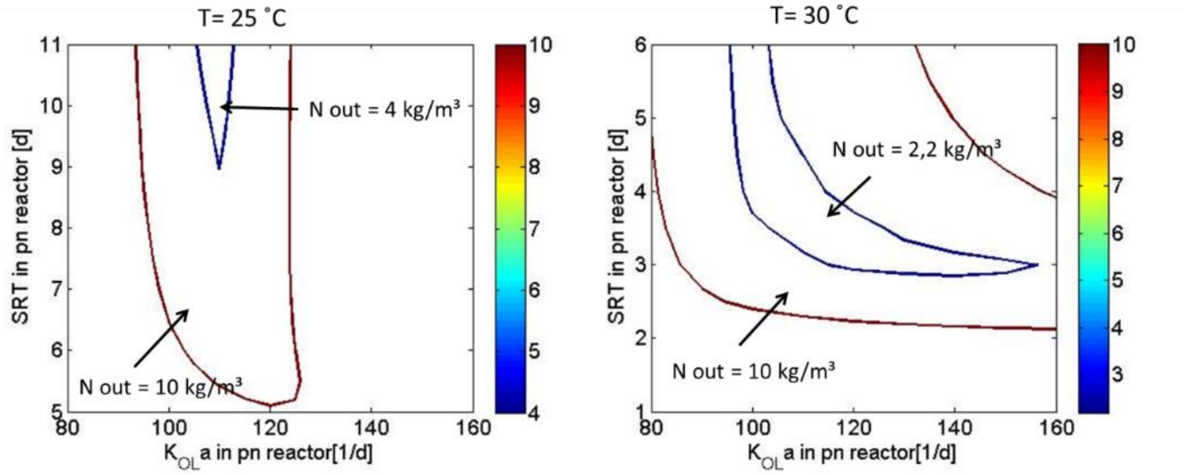

Figure 9. Effect of temperature on the relationship between SRT and KOLa at the required N effluent N concentration

Figure 9 indicates that the PN process is unable to reach the required effluent N concentration when operating at temperatures levels lower than 30˚C. Therefore, the temperature is fix at 30˚C while the influent N and COD concentration are varied as disturbances inputs.

The relationship between SRT and KOLa for the required effluent N concentration at specific N and COD concentration are obtained through simulation of the dynamical (Figure 10).

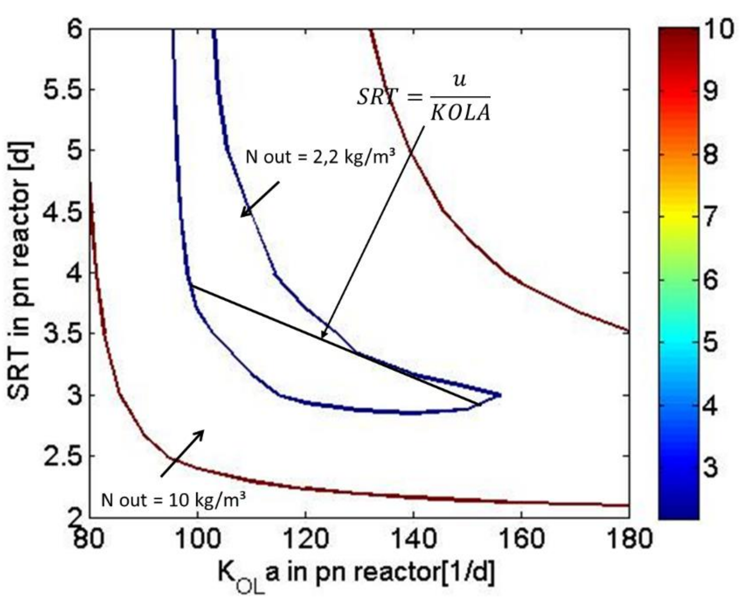

Figure 10. The relationship between SRT and KOLa at the required N effluent N concentration.

The relationship between SRT and KOLa for the required effluent N concentration at specific N and COD concentration is described using eq(3). This equation provide a wider KOLa ranges. The coefficients of this equation at specific COD and N concentrations and the control inputs ranges which provide the required effluent N levels is given in Table 4.

Table 4. The coefficients of the function of SRT and KOLa of the bioflocculation process at a specific disturbances levels

COD	N	u	SRT	KOLA
400	40	462	4,2-2,57	110-180
400	50	352	3,2-2,2	110-160
400	60	293,75	2,5-2,0	117,5-150
400	70	295,2	2,4-2,25	123-132
500	40	487,5	3,9-2,7	125-180
500	50	416	3,2-2,2	130-185
500	60	350	2,5-2,0	140-175
500	70	345	2,5-2,35	139-149
600	40	598,5	4,2-2,6	142,5-230
600	50	480	3,2-2,4	150-200
600	60	393,75	2,5-2	157,5-195
600	70	388,8	2,4-2,25	162-172
700	40	651	4,2-2,7	155-240
700	50	527	3,4-2,8	155-230
700	60	432	2,7-2,06	160-210
700	70	412,5	2,5-2,35	165-175

The control inputs particularly the KOLa levels are changed exclusively by the COD concentrations. The KOLa levels need to be lifted up when the influent COD concentration increase. The N concentration on other hand has an effect on the ranges of the control inputs that can be operated. The control inputs ranges which can be operated to achieve the required effluent N concentration reduce at the increase of the influent N concentration.

The function that link the coefficients and the disturbances is developed using eq(2) and eq(3). The contents of the polynomial second order function are presented in Table 5.

Table 5. The constants of the function that link the coefficient u and the disturbances levels.

Constants	0	1	2	3	4	5
ε	853.40 ±163.73	1.30 ±0.41	-28.3 ±4.04	-2.13 ±1.21**	0.25 ±0.03	-9.77 ±2.72*

:10⁻³

*****:10⁻⁴***

The obtained coefficient from the dynamic model u and the estimated coefficient u' with the polynomial function over the disturbances are shown in Figure 11 and 12.

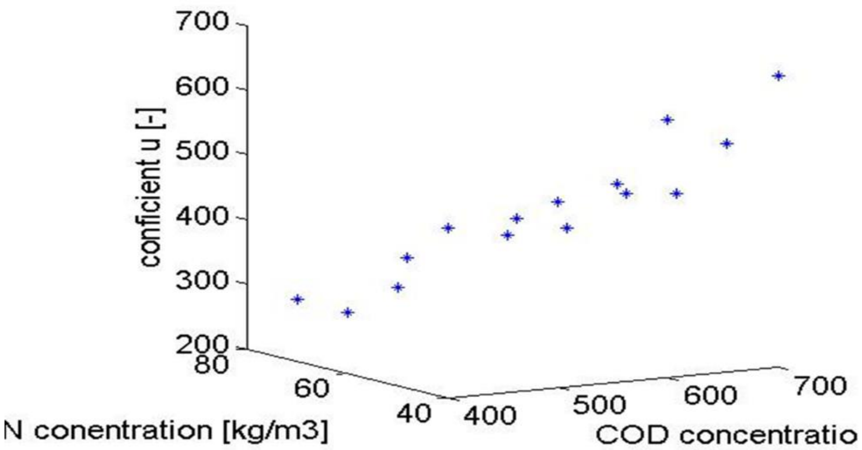

Figure 11. The coefficient u as a function of N and COD concentrations.

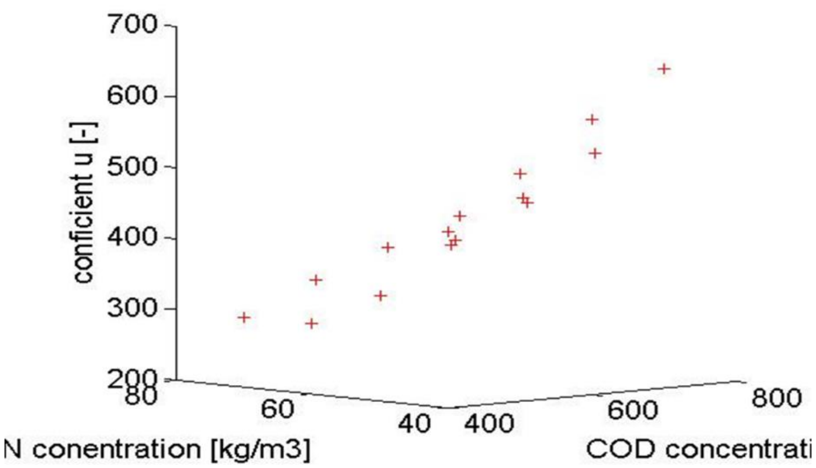

Figure 12. The calculated coefficient u' as a function of N and COD concentrations.

The calculated coefficients u' (blue) of different disturbances levels seem to fit the obtained coefficients form the dynamical model. Therefore, the constants can be used to describe the relationship between the SRT and KOLa in terms of the disturbance inputs (COD and N).

Evaluating the functions by inserting in the dynamical model

The functions describe the relationship between the SRT and KOLa in terms of the disturbance inputs (COD and T), after substitution of eq (2) in eq (1). These functions are evaluated by inserting into the dynamical model (***see Appendix C***).

First, we have tested whether the results shown in figure 4 can be reproduced. In figure 13, the results of the functions are compared with results given in figure 4 where the relation of the control inputs at methane production efficiency of 65% is presented.

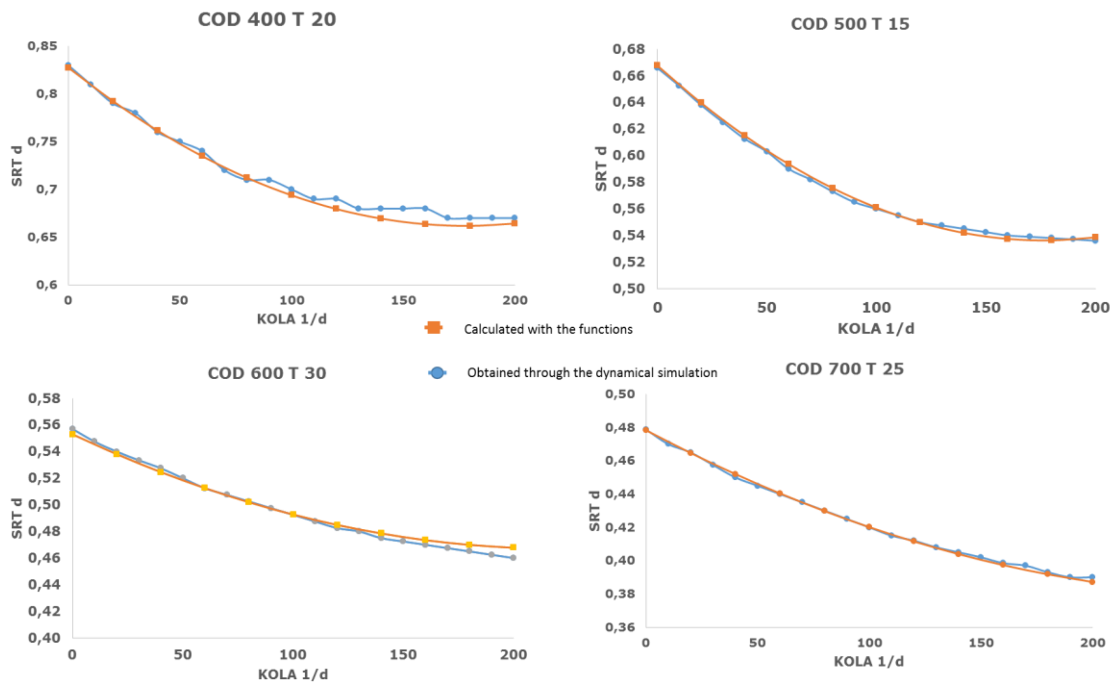

Figure 13. Comparison of the results calculated with the functions and the results obtained through the dynamical simulation.

The relationship of the SRT and KOLa determined with the functions fit those obtained through the dynamical simulation. Therefore, as a first check it can be concluded that the function can be used to deliver the required values of the control inputs of the BF process. Secondly, we have tested whether the functions provide the methane production efficiency of 65% for different COD and temperature levels (figure 14).

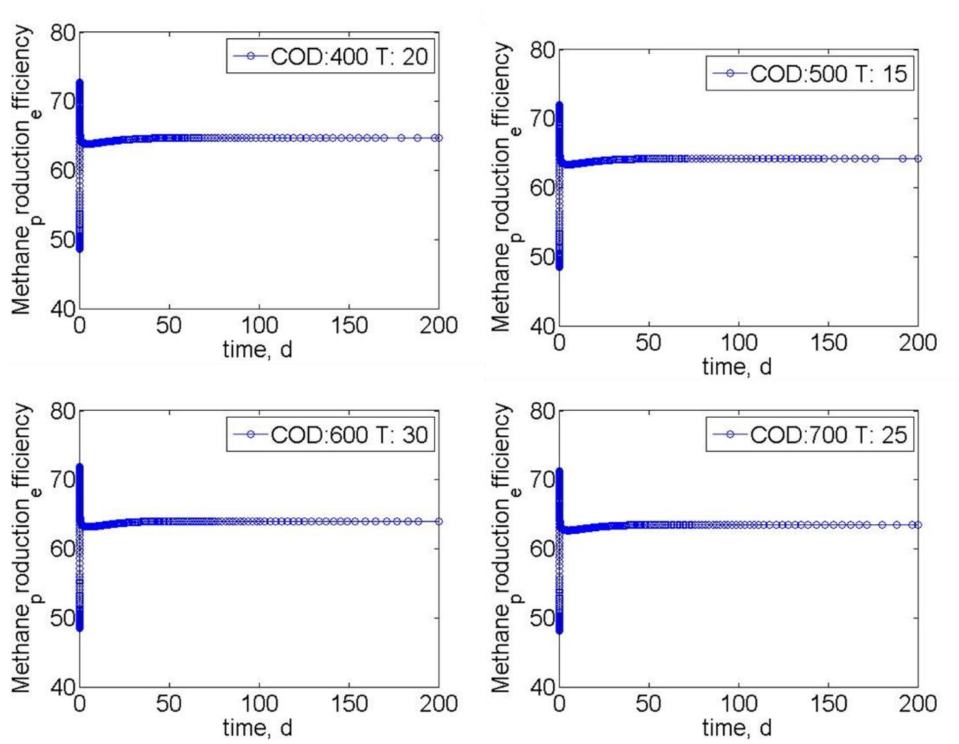

Figure 14. The methane production efficiency at different COD and temperature levels.

Figure 14 show that a methane production efficiency of approximately 65% is produced at different COD and temperature levels. This confirms that the functions give the relationship between SRT and KOLa at different COD and temperature levels and at methane production efficiency of 65%.

The same evaluation should be also done for the functions of the PN process and checked whether they provide the required SRT and KOLa values. Additionally the effect of the change of the KOLa of the BF process on the performance of the PN process need to be evaluated. The relationship between SRT and KOLa in the PN process could be influenced by the change of the KOLa in the BF process. It is also important to mention that the dynamical model should to be further calibrated using experimental data. After calibration, the method developed in this work can be applied in practice.

As first step, in the development of rules of thumb functions, the relation of the SRT to KOLa in the BF and PN processes has been derived. The functions consist of number of algebraic equation which give the SRT and the KOLa values of different disturbances levels at a certain operational condition. The drawback of these function is that they are exclusively valid for certain operational condition. However, these functions replace the differential equations and reduce the simulation time, significantly.

Conclusion

We have successfully developed a method where a simple model which describe static, non-linear control laws, is used for the implemention in practice. The simple model consist of a number of algebraic function that replace the differential functions in the dynamical model. The algebraic functions provide the SRT and KOLa values for different disturbances inputs levels.

The control inputs of the bioflocculation process and the partial nitritation are described using the algebraic functions. For the bioflocculation process; the SRT and the KOLa values are related to different disturbances levels at a methane production efficiency of 65%. As for the disturbances, the COD and temperature levels are varied while N concentration is fixed since the methane production is not depended on the N concentration. Also the SRT and the KOLa values, which ensure that the effluent quality will meet the new discharge levels is determined for the partial nitritation. Here, the N and COD concentration are varied while the temperature is fix at 30˚C since the PN process is unable to reach the required effluent N concentration when operating at temperatures levels lower than 30˚C.

The change of temperature has no effect on the control inputs of the BF process. The SRT and KOLa are influenced by the COD levels. To maintain the methane production efficiency at 65% the SRT needs to be decreased for increasing COD levels and KOLa.

In the partial nitritation process, The MBR system is more advantageous than the CSTR system as this system allow a wider SRT and KOLa ranges at the required effluent N levels. Operating in a wider SRT and KOLa range makes the process more robust and more reliable in practice.

The control inputs particularly the KOLa levels are influenced exclusively by the COD concentrations. The KOLa levels which ensure that the required effluent is achieved, increase when the COD concentrations is increased. The N concentration, however, has an effect on the ranges of the control inputs. The control inputs ranges which can be operated to achieve the required effluent N concentration become very narrow when the influent N concentrations increase. This make the process unstable and less safe. Consequently, for the partial nitritation and Anammox process advanced process control is needed.

Recommendation

The recommendation are as follows:

- The functions of the PN process need to be inserted into the dynamical model to check the robustness of the control inputs that ensures feasible effluent N concentration.

- The dynamical model should be calibrated using experimental data.

- The effect of the change of the KOLa of the BF process on the performance of the PN process need to be evaluated.

- The method could be used to provide a nonlinear, static control law for he anaerobic digester and Anammox processes.

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Appendixes

A. Disturbance combinations for the BF process

Table 6. Different COD concentrations and temperatures combinations

TEMP	COD
15	400
15	500
15	600
15	700
20	400
20	500
20	600
20	700
25	400
25	500
25	600
25	700
30	400
30	500
30	600
30	700

Table 7.Different COD concentrations and N concentrations combinations

COD	N
400	40
400	50
400	60
400	70
500	40
500	50
500	60
500	70
600	40
600	50
600	60
600	70
700	40
700	50
700	60
700	70

B. The math lab code of the functions of the BF process

```
alfa = [1.98E-05    -2.75E-07   -3.55E-08   2.50E-09    1.88E-11    1.40E-10];
beta = [5.81E-03    -3.15E-05   -1.13E-05   -7.50E-07   5.63E-09    7.40E-08];
gama = [1.88E+00    -9.65E-04   -3.42E-03   2.50E-05    2.06E-06    -2.00E-07];
a =  alfa(1)+ alfa(2)*TBF + alfa(3)*T_COD + alfa(4)*TBF^2 + alfa(5)*T_COD^2 +
alfa(6)*TBF*T_COD
b = beta(1)+ beta(2)*TBF + beta(3)*T_COD + beta(4)*TBF^2 + beta(5)*T_COD^2 + beta(6)*TBF*T_COD
c = gama(1)+ gama(2)*TBF + gama(3)*T_COD + gama(4)*TBF^2 + gama(5)*T_COD^2 + gama(6)*TBF*T_COD
```