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Some Considerations About Control of Multispecies Anaerobic Digestion Systems [⋆]

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Abstract: This paper presents a brief evaluation of a start-up strategy for multispecies anaerobic digestion systems modelled as two-step reaction systems, in which acidogenesis is described by Monod kinetics while the methanogenesis is described by Haldane kinetics. The start-up policy has been developed originally for single species systems with the aim of maximizing the biogas outflow rate. It consists of switching the dilution rate from minimum to maximum and then to the optimal value in order to bring the system from an arbitrary initial condition to the optimal setpoint. This start-up strategy is applied to the multispecies system using an averaged model, which is usually the only model that can be identified for a multispecies system, as measuring individual biomasses is quite difficult in practice. This study shows that the start-up policy leads to an efficient ecosystem, characterized by high outflow rate of biogas, even in the case of an inaccurate averaged model. It can be viewed as a robustness evaluation of the single species start-up strategy, as the process changes from the averaged kinetics to the kinetics of the winning species during species selection.

Keywords: biotechnology, waste treatment, nonlinear systems, optimality, bang-bang control

1. INTRODUCTION

Anaerobic digestion is one of the most popular process for the biological treatment of wastewater, as it not only removes the pollutants but also allows the production of biogas. Compared to the aerobic treatment, the anaerobic digestion provides several advantages among which the higher energy production and the substantially lower sludge production are the most important ones. In terms of process stability, anaerobic digestion still lags behind aerobic biological treatment or physico-chemical processes. Substantial expertise is required to operate such a process properly, as the operational point is not globally stable. Thus a good understanding of process dynamics and an efficient start-up strategy are required to safely drive the reactor towards an optimal operating point.

Many models for anaerobic digestion exist, the most used ones for system analysis and process control being the two-step reaction models. Commonly, the models assume that only one species perform the transformation, while in reality the conversion is carried out by a consortium of microorganisms, several hundreds of bacterial and archaeal species (Delbès et al., 2001). Thus the model represents an approximation of the real system by averaging the dynamics of the species present in the reactor at a certain moment, which may substantially differ from the real dynamics. Hence, reactor start-up is an even more delicate problem, as not only it has to bring the system to an operational point but it has to lead to a consolidated ecosystem in terms of treatment efficiency and maximization of biogas production.

Numerous studies regarding competition between species exist, but not many start-up strategies for multispecies anaerobic digestion systems have been developed. Recently, Masci et al. (2009) presented a selective start-up strategy, which drives the competition by regulating the volatile fatty acids concentration. The aim is to select the species with good performance in the standard operating mode of the process.

This paper evaluates the applicability and efficiency of a start-up strategy for the optimization of methane production in a multispecies anaerobic digestion system. This strategy has been developed for a single species model of the system (Sbarciog et al., 2011a,b). Two situations are illustrated: the case when an accurate averaged model is available and the case when the identified averaged model does not describe accurately the multispecies system. The start-up policy consists of switching the dilution rate between three levels to bring the system to a steady state characterized by a high outflow rate of biogas. On the one hand, the start-up strategy appears as a simple mean to build an efficient ecosystem by driving the competition between the species to select the ones able to enhance system productivity; on the other hand, this study may be seen as a robustness evaluation of the start-up strategy: as the selection process goes on, the system dynamics are better characterized by the kinetics of the favored species rather than the averaged kinetics.

This paper is organized as follows. The next section introduces the system models, whereas section 3 briefly summarizes the optimal control strategy. In section 4, simulation results are thoroughly discussed. Finally, section 5 draws conclusions and suggests research perspectives.

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2. THE SYSTEM MODELS

Anaerobic digestion systems are usually modelled as two-step reaction systems (Bernard et al., 2001), where the considered reactions are acidogenesis and methanogenesis. Commonly acidogenesis is characterized by Monod kinetics, while methanogenesis is characterized by Haldane kinetics. A mass balance on the chemostat system with n acidogenic species and m methanogenic species, leads to the mathematical model:

$$\dot{\xi}_1 = u(\xi_{in_1} - \xi_1) - a\sum_{i=1}^{n} r_1^i(\xi) \tag{1}$$

$$\dot{\xi}_2 = u(\xi_{in_2} - \xi_2) + c\sum_{i=1}^{n} r_1^i(\xi) - d\sum_{j=1}^{m} r_2^j(\xi) \tag{2}$$

$$\dot{\xi}_3^i = -u\xi_3^i + r_1^i(\xi) \qquad i = 1 \dots n \tag{3}$$

$$\dot{\xi}_4^j = -u\xi_4^j + r_2^j(\xi) \qquad j = 1 \dots m \tag{4}$$

where the reaction rates

$$r_1^i(\xi) = \mu_1^i(\xi_1)\xi_3^i \qquad r_2^j(\xi) = \mu_2^j(\xi_2)\xi_4^j \tag{5}$$

are characterized by the growth functions

$$\mu_1^i(\xi_1) = \mu_{m_1}^i \frac{\xi_1}{K_{s_1}^i + \xi_1} \qquad i = 1 \dots n \tag{6}$$

$$\mu_2^j(\xi_2) = \mu_{m_2}^j \frac{\xi_2}{K_{s_2}^j + \xi_2 + \dfrac{\xi_2^2}{K_{i_2}^j}} \qquad j = 1 \dots m \tag{7}$$

and the outflow rate of methane gas produced during transformations is:

$$Q(\xi) = q\sum_{j=1}^{m} \mu_2^j(\xi_2)\xi_4^j \tag{8}$$

In equations (1)-(4), ξ_1, ξ_2, ξ_3^i, ξ_4^j respectively represent the concentration of organic substrate, volatile fatty acid, acidogenic species i (with $i = 1 \dots n$) and methanogenic species j (with $j = 1 \dots m$). Thus, the state vector of the multispecies system is $\xi = \left[\xi_1 \; \xi_2 \; \xi_3^1 \; \dots \; \xi_3^n \; \xi_4^1 \; \dots \; \xi_4^m\right]^T$. u represents the dilution rate and ξ_{in_1}, ξ_{in_2} respectively represent the concentrations of organic substrate and of volatile fatty acids in the influent. $a, c, d > 0$ are the stoichiometric coefficients. $q > 0$ is the yield for the methane production.

An averaged model of the system (1)-(4) may be obtained by lumping the n types acidogens into one acidogenic species and the m types methanogens into one methanogenic species, with the growth functions

$$\mu_1^a(\xi_1) = \mu_{m_1}^a \frac{\xi_1}{K_{s_1}^a + \xi_1} \tag{9}$$

$$\mu_2^a(\xi_2) = \mu_{m_2}^a \frac{\xi_2}{K_{s_2}^a + \xi_2 + \dfrac{\xi_2^2}{K_{i_2}^a}} \tag{10}$$

Then, the averaged model becomes

$$\dot{\xi}_1 = u(\xi_{in_1} - \xi_1) - a\mu_1^a(\xi_1)\xi_3^a \tag{11}$$

$$\dot{\xi}_2 = u(\xi_{in_2} - \xi_2) + c\mu_1^a(\xi_1)\xi_3^a - d\mu_2^a(\xi_2)\xi_4^a \tag{12}$$

$$\dot{\xi}_3^a = -u\xi_3^a + \mu_1^a(\xi_1)\xi_3^a \tag{13}$$

$$\dot{\xi}_4^a = -u\xi_4^a + \mu_2^a(\xi_2)\xi_4^a \tag{14}$$

and the outflow rate of methane gas reads:

$$Q^a(\xi) = q\mu_2^a(\xi_2)\xi_4^a \tag{15}$$

For the equivalence between the multispecies model (1)-(4) and the averaged model (11)-(14), the following relationships must hold:

$$\xi_3^a = \sum_{i=1}^{n} \xi_3^i, \qquad \xi_4^a = \sum_{j=1}^{m} \xi_4^j \tag{16}$$

$$\mu_1^a(\xi_1) \cdot \xi_3^a = \sum_{i=1}^{n} \mu_1^i(\xi_1) \cdot \xi_3^i \tag{17}$$

$$\mu_2^a(\xi_2) \cdot \xi_4^a = \sum_{j=1}^{m} \mu_2^j(\xi_2) \cdot \xi_4^j \tag{18}$$

Denoting by $p_{a_i} = \xi_3^i/\xi_3^a$ the proportions of the acidogenic species ($i = 1 \dots n$) and by $p_{m_j} = \xi_4^j/\xi_4^a$ the proportions of the methanogenic species ($j = 1 \dots m$), with

$$\sum_{i=1}^{n} p_{a_i} = 1, \qquad \sum_{j=1}^{m} p_{m_j} = 1 \tag{19}$$

then (17), (18) become

$$\mu_1^a(\xi_1) = \sum_{i=1}^{n} p_{a_i} \cdot \mu_1^i(\xi_1) \tag{20}$$

$$\mu_2^a(\xi_2) = \sum_{j=1}^{m} p_{m_j} \cdot \mu_2^j(\xi_2) \tag{21}$$

2.1 Steady state analysis of the averaged model

A detailed analysis of the averaged model dynamics can be found in Sbarciog et al. (2010a), where it is shown that every system trajectory converges to a steady state lying on the plane $\Delta^a = \left\{\xi^a \in \mathbb{R}_+^4;\; \xi_1 + a\xi_3^a = \xi_{in_1};\; \xi_2 - c\xi_3^a + d\xi_4^a = \xi_{in_2}\right\}$

Depending on the magnitude of the dilution rate u and of the substrate concentrations in the influent ξ_{in_1}, ξ_{in_2}, the averaged model may possess up to six steady states, which can be roughly grouped in wash out equilibria (characterized by the wash out of either one or both microorganism types) and operational equilibria (characterized by the presence of both microorganism types). The analytical expressions and the stability properties of all equilibria can be found in (Sbarciog et al., 2010a).

2.2 Steady state analysis of the multispecies model

According to the competitive exclusion principle (CEP), first introduced by Hardin (1960), at most one of the acidogenic species and one methanogenic species will survive (Smith and Waltman, 1995). The winning species are the ones requiring the smallest amount of nutrient in steady state. This implies that the multispecies system has the same types of equilibria as the averaged model (or the single species system), all lying in the set

$$\Delta = \left\{\xi \in \mathbb{R}_+^{2+n+m};\; \xi_1 + a\sum_{i=1}^{n}\xi_3^i = \xi_{in_1},\right.$$
$$\left.\xi_2 - c\sum_{i=1}^{n}\xi_3^i + d\sum_{j=1}^{m}\xi_4^j = \xi_{in_2}\right\}$$

Their analytical expressions are similar to the ones of the single species model, where the concentrations of acidogenic and methanogenic bacteria are respectively replaced by vectors of the form $\left[0 \; \dots \; \xi_3^i \; \dots \; 0\right]^T \in \mathbb{R}_+^n$, $\left[0 \; \dots \; \xi_4^j \; \dots \; 0\right]^T \in \mathbb{R}_+^m$.

$i \in [1, n]$ and $j \in [1, m]$ indicate respectively the winning species.

3. OPTIMIZING CONTROL

An important aspect in controlling anaerobic digestion systems is represented by the maximization of biogas production. In this view, Sbarciog et al. (2011a,b) have presented a control strategy for single species systems. The strategy is based on the system properties and successfully approximates the solution of a classical optimal control problem for maximizing biogas production during the transient. The transient optimization is coupled with a steady state optimization, which allows to reach the equilibrium characterized by maximum biogas outflow rate.

The strategy proposes to drive the system from an arbitrary initial condition to the optimal steady state by operating the system as follows:

- minimum dilution rate (u_{min}) until the switching surface is reached;
- maximum dilution rate (u_{max}) until the target set is reached;
- optimal dilution rate (u_s); then the system settles down in the optimal steady state.

Minimum and maximum dilution rates and the target set are chosen based on the model characteristics, while the optimal dilution rate is the solution of a steady state optimization problem. One of the system stability boundaries is selected as switching surface, which can be accurately estimated using an algorithm such as described by Sbarciog et al. (2010b). It is assumed that the substrate concentrations in the influent are constant and known.

In this work, we apply the optimizing control strategy to the multispecies system (1)-(4) by determining the required key elements using an averaged model of the form (11)-(14). Details regarding the selection of u_{min}, u_{max}, the definition of the target set S and the calculation of u_s can be found in (Sbarciog et al., 2011b). Here, we evaluate to which extent this start-up procedure leads to a consolidated ecosystem in terms of biogas production maximization.

4. SIMULATION RESULTS

To evaluate the optimizing control strategy for the multispecies system, we consider further, without loss of generality, that three acidogenic species ($n = 3$) and three mehanogenic species ($m = 3$) are present in the reactor at start-up.

4.1 Accurate averaged model

Numerical values for the kinetic parameters of each species have been generated from the ones used by Sbarciog et al. (2011b). They are given in Table 1. Subsequently, an averaged model is identified for the multispecies system, where the parameters of the growth functions $\mu_1^a(\xi_1)$ and $\mu_2^a(\xi_2)$ are found from (20) and (21) using the function 'lsqcurvefit'. The following values have been assumed for the proportions of the species for both model identification and system simulation: $p_{a_1} = 0.2$, $p_{a_2} = 0.5$, $p_{a_3} = 0.3$, $p_{m_1} = 0.5$, $p_{m_2} = 0.2$, $p_{m_3} = 0.3$. The growth functions are shown in Figure 1, while the identified values of the kinetic parameters are: $\mu_{m_1}^a = 1.284$, $K_{s_1}^a = 11.297$, $\mu_{m_2}^a = 0.724$, $K_{s_2}^a = 14.291$, $K_{i_2}^a = 255.65$. The minimum dilution rate has been selected as $u_{min} = 0.3\text{day}^{-1}$, which guarantees for the averaged model the convergence to an operational point from any system initial condition characterized by the presence of both bacteria type ($\xi_3^a(0) > 0$, $\xi_4^a(0) > 0$). The maximum dilution rate has been chosen as $u_{max} = 0.49\text{day}^{-1}$, which ensures the occurrence of the operational equilibria, while the optimal dilution rate has been calculated as $u_s = 0.4728\text{day}^{-1}$. The corresponding optimal steady state of the averaged model is $\xi_s^a = [\,6.58\ 36.79\ 0.79\ 0.86\,]^T$ and the outflow rate of biogas produced in this steady state is $Q(\xi_s^a) = 184.28$.

Table 1. Numerical values of the parameters for the multispecies system - case 1

Stoichiometric	a d	42.14 268 mmole/g	c q	116.5 mmole/g 453 mmole/g
Acidogens	$\mu_{m_1}^1$ $\mu_{m_1}^2$ $\mu_{m_1}^3$	1.2 day^{-1} 1.56 day^{-1} 0.96 day^{-1}	$K_{s_1}^1$ $K_{s_1}^2$ $K_{s_1}^3$	7.1 g/l 21.3 g/l 2.13 g/l
Methanogens	$\mu_{m_2}^1$ $\mu_{m_2}^2$ $\mu_{m_2}^3$	0.74 day^{-1} 1.258 day^{-1} 0.518 day^{-1}	$K_{s_2}^1$ $K_{s_2}^2$ $K_{s_2}^3$ $K_{i_2}^1$ $K_{i_2}^2$ $K_{i_2}^1$	9.28 mmole/l 41.76 mmole/l 15.776 mmole/l 256 mmole/l 128 mmole/l 384 mmole/l

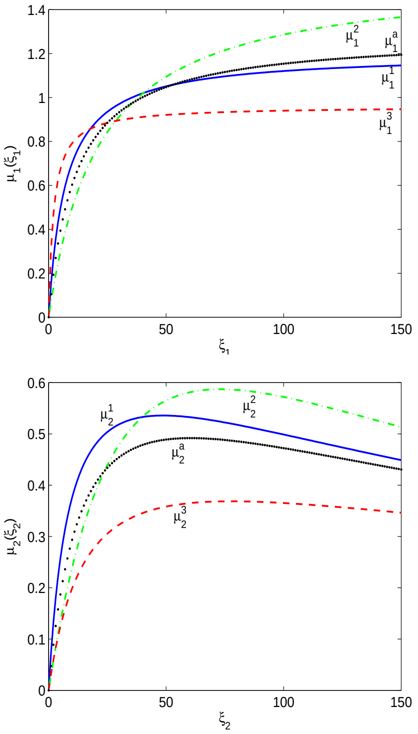

Fig. 1. Growth functions of the acidogenic and methanogenic species and of the averaged model - case 1

Table 2 presents the optimal dilution rates and the corresponding maximum biogas outflow rates for each possible combination of the acidogenic and methanogenic species. It is worth noting that, except the cases involving the third methanogenic species, the averaged model predicts a lower biogas outflow rate achievable with a lower dilution rate than the optimal ones calculated for species combination. Note also that these optimal dilution rates are higher than the selected u_{max}, which indicates that if wash out occurs (ie. the third methanogenic species has been selected) then this is due to the species selection process and not to inadequately chosen dilution rates.

Table 2. Optimal dilution rates / optimal outflow rates of methane for pairs of acidogenic and methanogenic species - case 1

	m_1	m_2	m_3
a_1	0.5179 / 211.005	0.5551 / 208.870	0.3478 / 138.886
a_2	0.5141 / 198.529	0.5469 / 194.431	0.3457 / 133.695
a_3	0.5197 / 218.044	0.5590 / 217.221	0.3488 / 141.639

Figure 2 shows the phase portrait of the averaged model (11)-(14) on the plane Δ^a, controlled with the proposed optimization technique. This illustrates the case of a single specie system for which an accurate model is available. Figure 2 shows the position of the acidification and the coexistence steady states for the system operated with u_s, the physical boundaries in continuous lines, the switching curve in dashed line and the target set around the optimal equilibrium. The operation is intuitively represented on the right hand side of the phase portrait for one of the system trajectory originating in an initial state on the physical boundary: the system is operated with u_{min} until the trajectory reaches the switching curve, then the dilution rate is changed to u_{max} and the system is operated with the new value until the target set is reached; in the end the dilution rate is set to the optimal value and the system converges to the optimal setpoint.

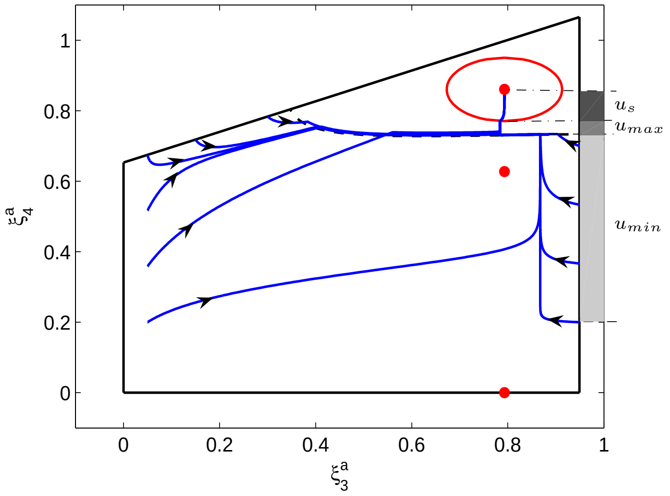

Fig. 2. Controlled phase portrait of the averaged model on the plane Δ^a - case 1

Figure 3 shows the phase portrait of the controlled multispecies system (1)-(4), where the total amount of methanogens is plotted against the total amount of acidogens. The steady states of the averaged model for $u = u_s$ are illustrated with circles, while the steady states of the multispecies system for the same dilution rate are illustrated with squares. Figure 4 illustrates the time evolution of the biomasses and the biogas production in the controlled averaged system respectively in the controlled multispecies system. The species a_3 wins the competition among the acidogens, while the species m_1 wins the competition among the methanogens. There is no particularity in the species selection process in this case, as for each dilution rate level, the species a_3 and m_1 need the smallest amount of ξ_1 respectively ξ_2. This can be seen in Figure 1. Compared to the single species system (illustrated here by the averaged model), the final steady state is reached much faster and higher biogas outflow rate and COD consumption (result not shown in Figure 4) are obtained in the multispecies system. According to Table 2, the species combination which leads to the highest biogas production in steady state is the one which was selected using the optimization strategy. However, less biogas is produced due to the fact that the system is operated with the optimal dilution rate computed from the averaged model and not the one given in Table 2.

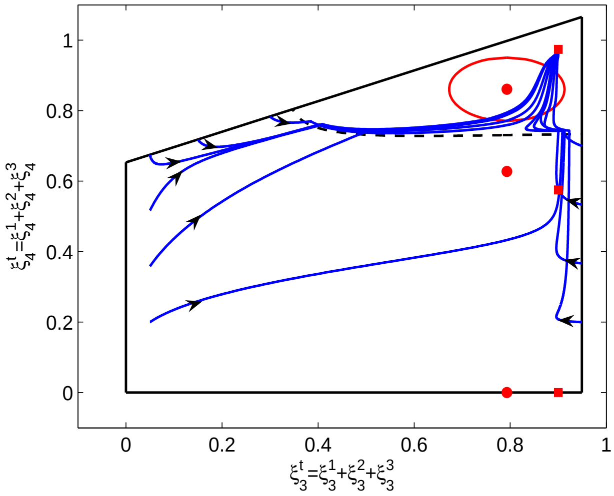

Fig. 3. Controlled phase portrait of the multispecies system - case 1

4.2 *Inaccurate averaged model*

Identifying an accurate averaged model for the multispecies system is a difficult task due to the numerous species composing the ecosystem and the permanent interactions between them. In this section we illustrate the efficiency of the optimization strategy by using an averaged model, which was not build based on the relationships (20) and (21). The kinetics of the averaged model shown in Figure 5, have been chosen such that they are of the same order of magnitude as the kinetics of the multispecies system, without assuming any species proportions. The parameters of the averaged model are: $\mu_{m_1}^a = 1$, $K_{s_1}^a = 12.5$, $\mu_{m_2}^a = 0.95$, $K_{s_2}^a = 9$, $K_{i_2}^a = 145$, while the kinetic parameters of the multispecies system are given in Table 3. For the simulation of the start-up, the proportions have been selected as $p_{a_1} = 0.4$, $p_{a_2} = 0.3$, $p_{a_3} = 0.3$, $p_{m_1} = 0.3$, $p_{m_2} = 0.4$, $p_{m_3} = 0.3$.

Table 3. Numerical values of the parameters for the multispecies system - case 2

Acidogens	$\mu_{m_1}^1$	1 day^{-1}	$K_{s_1}^1$	7 g/l
	$\mu_{m_1}^2$	0.9 day^{-1}	$K_{s_1}^2$	20 g/l
	$\mu_{m_1}^3$	0.73 day^{-1}	$K_{s_1}^3$	2 g/l
Methanogens	$\mu_{m_2}^1$	0.9 day^{-1}	$K_{s_2}^1$	6 mmole/l
	$\mu_{m_2}^2$	1.25 day^{-1}	$K_{s_2}^2$	15 mmole/l
	$\mu_{m_2}^3$	0.85 day^{-1}	$K_{s_2}^3$	10 mmole/l
			$K_{i_2}^1$	150 mmole/l
			$K_{i_2}^2$	100 mmole/l
			$K_{i_2}^1$	200 mmole/l

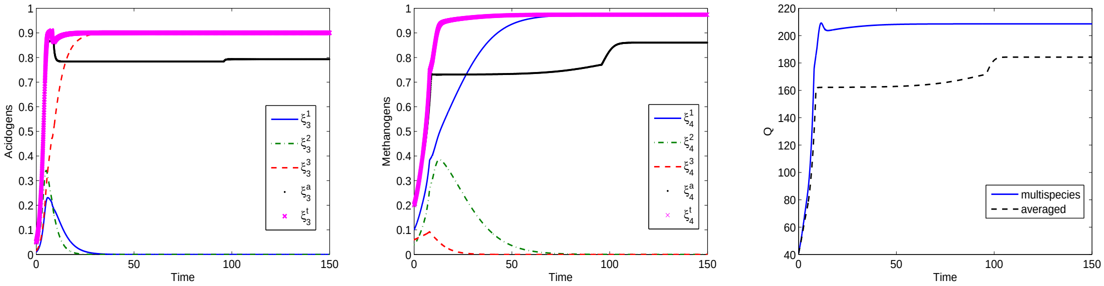

Fig. 4. Time evolution of the biomasses and the biogas production for a controlled trajectory - case 1

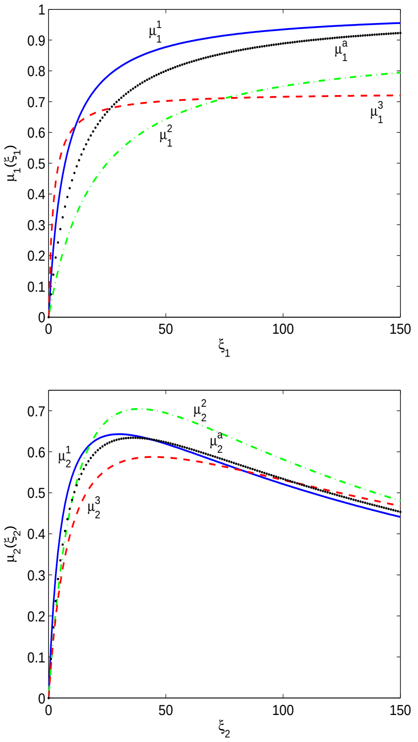

Fig. 5. Growth functions of the acidogenic and methanogenic species and of the averaged model - case 2

Table 4. Optimal dilution rates / optimal outflow rates of methane for pairs of acidogenic and methanogenic species - case 2

	m_1	m_2	m_3
a_1	0.6246 / 247.290	0.6665 / 251.830	0.5651 / 222.843
a_2	0.5182 / 176.659	0.5173 / 174.281	0.4971 / 169.316
a_3	0.6057 / 248.671	0.6147 / 247.954	0.5623 / 228.809

As in the previous case, the minimum dilution rate has been selected as $u_{min} = 0.3\text{day}^{-1}$, ensuring thus the convergence of the averaged model to an operational point from any system initial condition characterized by the presence of both bacteria type. The maximum dilution rate has been chosen as $u_{max} = 0.63\text{day}^{-1}$, which ensures the occurrence of the operational equilibria, while the optimal dilution rate has been calculated as $u_s = 0.599\text{day}^{-1}$. The corresponding optimal steady state of the averaged model is $\xi_s^a = [\,18.67\ 20.13\ 0.5\ 0.8\,]^T$ and the outflow rate of biogas produced in this steady state is $Q(\xi_s^a) = 217.08$.

Table 4 presents the optimal dilution rates and the corresponding maximum biogas outflow rates for each possible combination of the acidogenic and methanogenic species. Except for the combinations involving the acidogenic species a_2, all the others provide higher biogas outflow rate in steady state than the one predicted by the model. Noticeable in this case is the fact that the optimal dilution rate for the pair a_1-m_2 is higher than u_{max}.

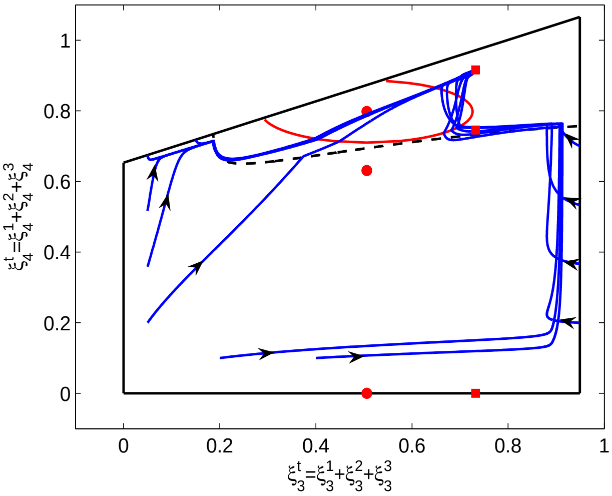

Fig. 6. Controlled phase portrait of the multispecies system - case 2

Figure 6 shows the phase portrait of the controlled multispecies system as total amount of acidogens versus total amount of methanogens. The steady states of the averaged model for $u = u_s$ are illustrated with circles, while the steady states of the multispecies system for the same dilution rate are illustrated with squares. Figure 7 shows the time evolution of the biomasses and the biogas production in the controlled averaged system respectively in the controlled multispecies system. In this case, the different levels of the dilution rate favor different species in the group: for u_{min}, the species a_3 and m_1 are favored, while for u_{max} the species a_1 and m_2 are promoted. In the end, the species a_3 wins the competition among the acidogens, while the species m_1 wins the competition among the methanogens as they require the smallest amount of ξ_1 respectively ξ_2 for u_s. This may be noticed in Figure 5. Now, the species selection process is slower than the averaged model dynamics, however the biogas outflow rate and the COD consumption reach levels very close to their steady states as fast as the averaged model. In steady state, the biogas outflow rate produced by the multispecies system is very close to the optimal value of the pair a_3-m_1, as the optimal dilution rate for this pair and u_s, the optimal dilution rate of the averaged model, assume similar values (see Table 4).

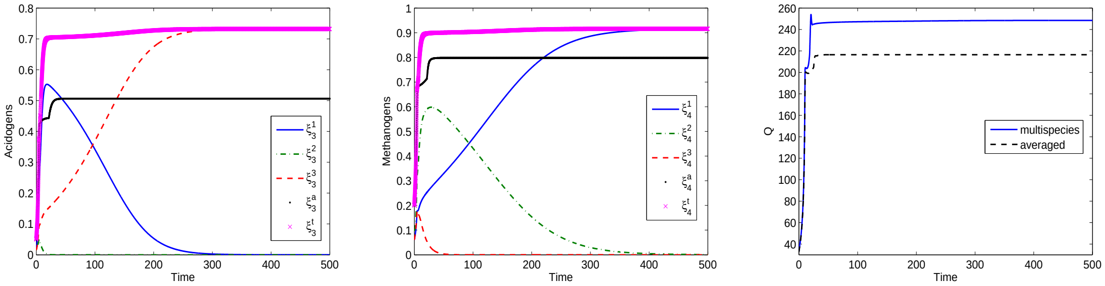

Fig. 7. Time evolution of the biomasses and the biogas production for a controlled trajectory - case 2

4.3 Discussion

The simulation results presented in the previous section for both the accurate and inaccurate averaged models show that a meaningful steady state is reached, characterized by a higher biogas outflow rate and higher COD consumption than the ones predicted by the averaged model. An important question is whether or not the start-up procedure leads to the selection of the most efficient species in terms of biogas production. It can be proved, using the analytical expressions of the equilibrium points, that the acidogenic and methanogenic species winning the competition for $u = u_s$ are the most efficient ones at this dilution rate among the species present in the reactor. These are the species needing the smallest amount of substrates in steady state, which already implies a high treatment efficiency, as the amount of untreated pollutants (substrates leaving the reactor) is at the lowest possible level. The amount of biogas produced in steady state is given by the product between $q \cdot u_s$ and the concentration of methanogenic bacteria, which won the competition. This concentration is the highest among all methanogenic species (see the expression of system equilibria in (Sbarciog et al., 2010a)), which implies that the biogas outflow rate is maximum. Note that the species efficiency is evaluated with respect to the dilution rate levels chosen based on the averaged model. In reality, higher biogas outflow rate for a higher dilution rate may be obtained by selecting another pair of species, such as a_1-m_2 in Table 4. However, kinetics of the individual species are not available in practice, the only known kinetics are the ones of the identified averaged model. We conclude that the competitive exclusion is the best selection process of the most efficient species in generating the highest amount of biogas at the dilution rate u_s. However, a crucial condition is that these species are present in the reactor in the final stage of the control strategy, ie. they have not been washed out before switching the dilution rate to u_s. Hence, a study regarding the long run coexistence of the species, such as the one presented by Rapaport et al. (2009) for species with Monod kinetics, is necessary to estimate the time the species coexist and eventually adjust the switching moments for the dilution rate accordingly.

5. CONCLUSIONS

In this paper a brief evaluation of a start-up policy for multi-species anaerobic digestion systems has been presented. The simulation results obtained using both accurate and inaccurate averaged kinetics indicate that this strategy leads to a consolidated ecosystem, with enhanced productivity compared to the one predicted by the averaged model. However, further investigations are needed to have a complete view on the method potentiality. Of particular importance is the estimation of the time span the species can coexist in the reactor, which may play a prominent role in some cases for the selection of the most efficient species.

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