Operation of an innovative WWTP with environmental objectives. A model-based analysis

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Abstract: Operation of wastewater treatment plants can be subjected to economic, energetic and/or environmental objectives, besides the compliance with effluent limits. As trade-offs between different objectives are frequently unavoidable, model based analysis can assist in decision making and give further insight on the effect of the operating conditions. Furthermore, as new wastewater treatment technologies have appeared in the latest years, model-based analysis is needed to ascertain what the advantages of the new technologies are. We demonstrate here how to assess and operate an innovative WWTP according to different objectives with case-study based on a real innovative pilot plant. The plant features the use of denitrifying anaerobic methane oxidation (DAMO) bacteria to deplete methane from digestate. Furthermore, given the slow growth rate of the system and the tendency to create complex syntrophic environments, the use of a model becomes a keystone to operate these reactors.

Keywords*:* plantwide operation; wastewater treatment; N-DAMO bacteria; methane release; optimisation

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1. INTRODUCTION

The operation of a wastewater treatment plant (WWTP) must deal with a hierarchy of objectives which are often in conflict, leading to trade-off solutions. In general, the first objective that must be fulfilled is the requirements in the effluent which depend on whether the WWTP treats urban or industrial water, which is the receiving water body and, of course, the regulation applying to the area. Effluent limits include almost universally COD and solids, in most cases nowadays nutrients (phosphorous and nitrogen compounds) and in some countries emerging pollutants are now being regulated as well. When effluents limits are fulfilled, a plant manager will seek to reduce the energy expenses as, together with the chemicals, they represent the major part of the operating cost for a WWTP. Only on top of these two layers of objectives, would environmental goals be implemented. The main negative impacts of WWTP identified include sludge disposal, electricity and chemicals consumption for operation and direct greenhouse gas (GHG) emissions. The reduction of GHG emissions has only recently been tackled in the last years due to the difficulty in characterizing, quantifying and modelling those emissions.

In a number of cases, the major environmental impact of a WWTP is related to its energy use; therefore, reducing the energy consumption also leads to a better environmental record provided that the effluent limits are respected. Hence, minimising environmental impact and the energy consumption constitute a non-zero sum game (i.e. win-win). However, in cases where energy use is not the main contributor to the environmental impact, the optimisation of both criteria tends to be a zero-sum game and trade-offs between the two objectives are unavoidable.

Running a WWTP at low GHG emissions is admittedly not an easy task, especially while respecting the effluent limits and keeping the operating costs controlled. This task becomes even more complex given the common structure of incentives and objectives in a WWTP: operators are evaluated for keeping the process running and respecting the effluent limits while, it is the plant manager and/or chief operator who must focus on minimising the operating costs (Rieger and Olsson 2014). In this context, simulation and model based analysis appears as an essential tool for assisting in decision making on how to operate, manage and control the plant.

We address here the issue of operating an innovative plant with different objectives (effluent, energy and environment) by using a model-based analysis of the process. We use as a case-study an innovative process patented at the University of Santiago de Compostela (SIAM, Buntner et al. 2013) To demonstrate the methods and tackle the GHG emission as an environmental impact, we focus on reducing the release of methane by avoiding downstream stripping of digestate, the main contributor to methane release with biogas leaks and sludge disposal.

This paper is organised as follows. First the model of the plant is described, together with indicators of the plant performance. Then the operating window is mapped and the different operating regions are characterised in terms of activity, objectives and microbial diversity. Finally, conclusions about how to operate the plant in different scenarios and proposals to implement a plantwide control are given.

2. MODEL AND PLANT DESCRIPTION

2.1 *Plant description*

An innovative pilot plant located at the University of Santiago de Compostela (Spain) was chosen as a case study. The plant (fig. 1) is a novel two-stage MBR process referred to as SIAM, (Spanish acronym for *Integrated system of methanogenic anaerobic reactor and membrane bioreactor for COD and nitrogen removal in wastewater)*. The plant and the operating conditions are described in detail elsewhere (Buntner *et al*. 2012) and summarised here for the sake of completeness. The influent is characterised by a high concentration of methane (25 mg CH_4/L), corresponding to the saturation from a psychrophilic UASB reactor at 17 ^oC. Apart from methane, there are 30 mg/L of soluble COD, 30 mg/L of particulate COD, 55 mgN/L of total ammonium and 25 mgN/L of total nitrite.

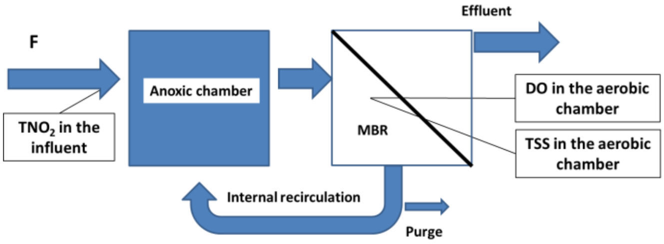

Fig. 1. Section of the SIAM plant studied. The influent is a digestate from an UASB reactor.

The design of the plant enhances the removal of methane from the anaerobic digestate and thereby avoids the stripping to the environment. Methane can be used as a source of electrons by the following microbial groups: denitrifying anaerobic methane oxidation (DAMO) process, by aerobic methane oxidizers (AMO) or by syntrophic consortia such as anaerobic methanogenic archaea (ANME) and sulphate-reducing bacteria (SRB).

2.2 *Plant model*

The process is modelled as two stirred tank reactors in series to represent the anoxic and the aerobic chamber. The aerobic chamber features a membrane which is modelled as having total rejection of particulate compounds and no rejection of soluble compounds. The mass balance of each compound is expressed by:

$$\frac{dC_{ij}}{dt} = D_j\left(C_{ij}{}^{IN} - C_{ij}\right) + r_{ij} + j_{ij} \qquad (1)$$

where C_{ij} is the concentration of compound *i* in tank *j*, $C_{ij}{}^{IN}$ is the concentration of compound *i* in the inflow of tank *j*, r_{ij} is the net generation by reaction and j_{ij} stands for the mass transfer to and from the gas phase. D_j is the dilution rate which is defined as:

$$D_j = \frac{F_j{}^{IN}\,\rho_j}{M_j} \qquad (2)$$

where $F_j{}^{IN}$ is the inflow of tank *j*, M_j is the mass hold-up of tank *j* and ρ_j is the density of tank *j*. As the tank outflow is determined by overflow, the volume of each tank remains constant. Furthermore, approximating the density of the hold-up as close to the density of water, *Mj* can be assumed as constant.

The model includes 21 states per chamber, namely the total mass and:

- 9 soluble compounds, namely dissolved oxygen, soluble COD, dissolved nitrogen, total ammonium nitrogen, total nitrite nitrogen, nitrate, soluble inerts, total inorganic carbon(TIC) and dissolved methane.
- 10 particulate compounds, namely particulate inerts, particulate COD, heterotrophs (Xh), storage product (Xsto), ammonium oxidizing bacteria (AOB), nitrite oxidizing bacteria (NOB), DAMO archaea (Xda), DAMO bacteria (Xdb), anaerobic ammonium oxidizing bacteria (Xan or anammox), aerobic methane oxidizers (Xamo) and total solids (TSS)

The microbial kinetics are modelled by 25 processes that are briefly summarised here. The heterotrophic metabolism was modelled using the activated sludge model no. 3 (Henze *et al*. 2003) with the modification added by Iacopozzi *et al.* (2007) to include two step nitrification-denitrification as nitrite is the substrate of anammox and DAMO bacteria. The biological reactions of AOB, NOB and anammox were modelled as in Vangsgaard et al. (2012) using the unionized form of ammonium and nitrous acid as true substrates. The model of DAMO archaea and bacteria was taken from Chen *et al.* (2014) but modified in order to include the oxygen inhibition results obtained by Luesken et al. (2012). Finally, the aerobic methane oxidizers were modelled as in Arcangeli and Arvin (1998).

Only O_2, CO_2, CH_4 and NH_3 are considered to be volatile, and therefore can be transferred to and from the aerating flow (transfer with the headspace is considered as negligible). The flow rate of compound, in mass per volume and time, is given by:

$$j_i = k_L a\,(Mw_i\,H_i\,P_i - S_i) \qquad (3)$$

where k_La is the specific mass transfer coefficient, Mw_i is the molecular weight, H_i is Henry's constant, P_i is the partial pressure of *i* in the gas phase and *Si* is the concentration of the volatile compound. Note the difference between S_i and C_i, e.g., C_i represents the total ammonium plus ammonia concentration whereas S_i only stands for the concentration of ammonia, which is the only volatile form.

2.4 *Modelling of aeration and energy consumption*

The relation between the air flow rate and the oxygen transfer is modelled as reported by Martin *et al.* (2011)

$$Q_{air} = \frac{j_{O2}\,V_{aer}}{x_{O2}\,\rho_{air}\,\alpha\,\beta\,\gamma\,OTE} \qquad (4)$$

where Q_{air} (in m^3/d) is the air flow rate V_{aer} is the volume of the aerobic chamber, x_{O2} is the volume fraction of oxygen in air, ρ_{air} is the density of air, α is the mass transfer ratio between clean water and wastewater, β and γ are efficiency parameters ($\beta = 0.95$; $\gamma = 0.89$) and OTE is the oxygen transfer efficiency ($OTE = 0.02$).

According to the same authors, parameter α is related with the solids concentration in water as follows:

$$\alpha = \exp(-0.082\,TSS) \qquad (5)$$

The energy needed for aeration is calculated as the adiabatic compression work, given by:

$$W = \left[\left(\frac{P + \rho g h}{P}\right)^{\frac{\delta - 1}{\delta}}\right] \frac{Q_{air} P}{\eta} \frac{\delta}{\delta - 1} \qquad (6)$$

where W is the power (in J/d) P is the atmospheric pressure, h is the height of the tank, δ is the heat capacities ratio (7/5 for air), and η is the blower efficiency.

2.5 *Definition of objectives*

As discussed previously, it is possible to define objectives of different kind. Considering that this plant treats reject streams and it is not aimed to discharge directly into a water body, the following performance indicators can be defined:

i) The ratio of nitrogen removed

$$NRemoval = 1 - \frac{(NH_3 + NO_2 + NO_3)_{eff}}{(NH_3 + NO_2 + NO_3)_{inf}} \qquad (7)$$

where subscript *eff* stands for the effluent concentration and *inf* for the influent concentration.

ii) The methane that is removed, understood as the amount of methane that was eliminated by consumption of the microbial groups over the methane that entered the plant:

$$CH_4Removal = \frac{(-r_{CH4}\,V)_{anox} + (-r_{CH4}\,V)_{aer}}{(CH_4)_{inf}} \qquad (8)$$

where subscript *anox* stands for the anoxic chamber and *aer* stands for the aerobic chamber.

iii) The carbon footprint (in g CO_2eq/m^3 of influent), which includes the methane that has not been removed (and reaches the environment by stripping or from the effluent) and the electricity used for aeration. Other energy consuming equipment, such as pumps were found as negligible in this process.

$$CF = \frac{\left[j_{CH4} + (F\,C_{CH4})_{eff}\right] e_{CH4} + W e_{elec}}{F_{inf}} \qquad (9)$$

where e_{CH4} is the methane emission factor (e_{CH4} = 34 g CO_2eq/gCH_4; Myhre et al. 2013) and e_{CO2} is the electricity emission factor (e_{CO2} = 0.487325 g CO_2eq/kWh).

iv) Finally, the nitrogen removed per kg of CO_2eq released (in kgN/kg CO_2eq), is defined as:

$$NCF = \frac{(NH_3 + NO_2 + NO_3)_{inf}\ NRemoval}{CF} \qquad (10)$$

3. MAP OF OPERATIONAL REGIONS

Two degrees of freedom for operation were considered for the study: the DO level and the total concentration of solids at the aerobic chamber (Fig.1). These two variables can be controlled by manipulating respectively the flow of aeration and the purge flow. The third potential degree of freedom, namely the recirculation flow, was found not to have a strong impact on the objectives in the window of operation considered and it is therefore not included in this study. The nominal value of the operating conditions in the pilot plant is the following: DO = 1 mg/L; TSS = 14 gCOD/L and R =3 times the feed flowrate. The window of operation explored is bounded by the following values DO_{min} = 0.8 mg/L to ensure mixing in the aerobic chamber; DO_{max} = 2 mg/L; TSS_{min} = 1.5 gCOD/L and TSS_{max} = 15 gCOD/L as a larger concentration of solids would increase considerably the energy expenses related to aeration and would lead to membrane fouling.

The effect of the two variables on the removal of nitrogen can be seen in Fig. 2. At low TSS, there is a low amount of nitrogen removed (between 15-20% of the total) by heterotrophic denitrification. The nitrogen removal remains constant in a wide area caused by COD limitation. In effect, as the COD provided to the reactor that can be used by heterotrophs is scarce, the available ammonium is converted autotrophically into NO_x but denitrification cannot take place further. When the level of TSS goes beyond a certain threshold (around 12 gCOD/L), slowly growing populations such as DAMO archaea and bacteria or anammox bacteria can thrive and perform the denitrification using methane (DAMO route) or ammonia (anammox) as the electron donor.

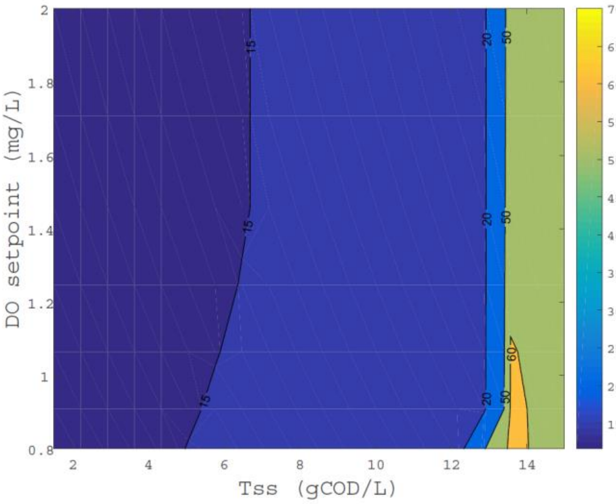

Fig. 2. Percentage of nitrogen removed (isolines in %) w.r.t. the level of dissolved oxygen and total solids in the aerobic chamber.

The different fates of methane in the plant according to the operating conditions can be seen in Fig. 3.Up to the threshold of 10-12 gCOD/L TSS, the depletion of methane depends on the levels of DO since it is used by the aerobic methane oxidizers (AMO bacteria) as an electron acceptor. At higher TSS values, the level of DO does not have any longer an effect since the DAMO route (anaerobic) can be used to remove methane.

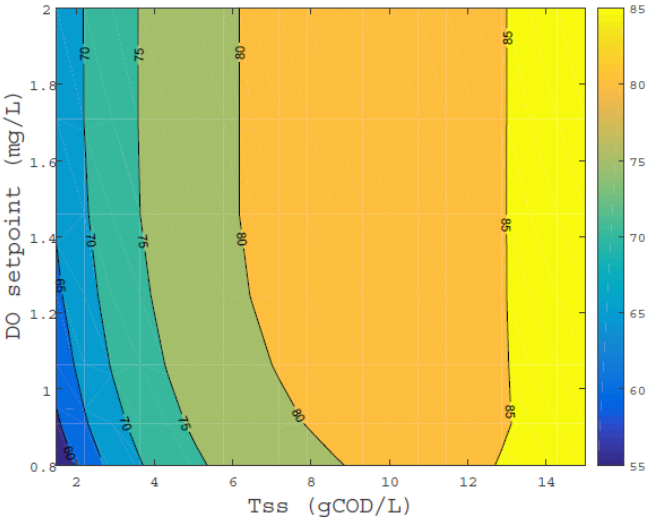

Fig. 3. Percentage of methane not released to the environment (isolines in %) w.r.t. the level of dissolved oxygen and total solids in the aerobic chamber.

Focusing on more complex objectives, the total carbon footprint of the plant depends highly on both the TSS and the DO level (Fig. 4). Up to 6-8 gCOD/L TSS two contributions to eq. (9) cancel each other: the decrease in the release of methane is compensated by higher energy consumption caused by increasing aerating flow needed to sustain the desired DO level. Between 8-12 gCOD/L TSS the carbon footprint increases steadily as the energy needs keep increasing while unreleased methane level barely evolves. From 12-14 gCOD/L TSS two regions can be distinguished: a region with decreasing carbon footprint at low oxygen levels and another region with increasing carbon footprint at high oxygen levels. The region of low oxygen level is dominated by the activity of bacteria which follow anaerobic or anoxic routes (DAMO bacteria and anammox), which displace the activity of obligate aerobes (heterotrophs and nitrifying populations).

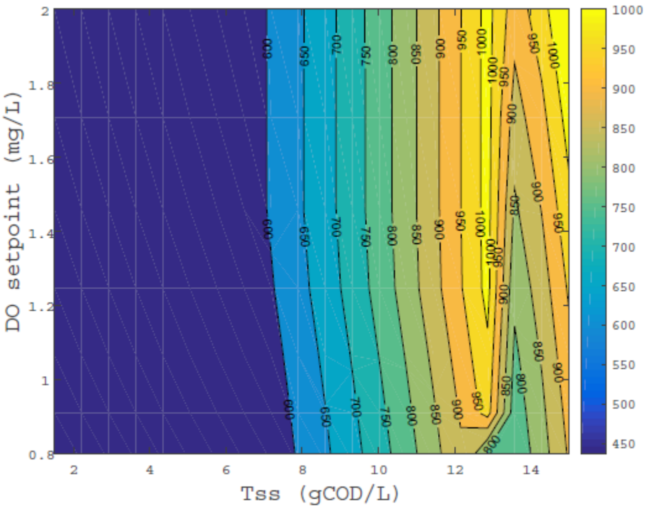

Fig. 4. Carbon footprint of the plant (isolines in g CO_2eq /m^3 treated water) w.r.t. the level of dissolved oxygen and total solids in the aerobic chamber.

Finally, merging both the nutrient removal objective and the environmental objective it is possible to find the operating conditions that would allow removing nitrogen at the lowest carbon footprint (Fig. 5).

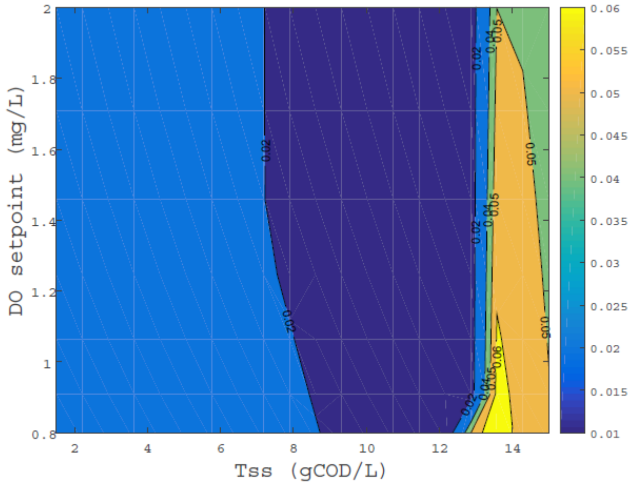

Fig. 5. Nitrogen removed per kg of CO_2eq (isolines in kgN/ kg CO_2eq) w.r.t. the level of dissolved oxygen and total solids in the aerobic chamber.

Studying the microbial group diversity (Fig. 6), it can be seen the shift seen in the operating objectives at around 12 gCOD/L TSS: the microbial diversity changes from fast growing bacteria to slowly growing bacteria. Fig. 6 only shows the microbial populations in the anoxic chamber but given the high rate of recirculation, the populations are the basically the same in the two chambers (although their activities are not necessarily the same)

Given the large amount of methane in the influent, methanotrophs are present in all the regions of operation. At high TSS concentration, they are however displaced by competition with the DAMO bacteria for methane. This is in general preferable for two reasons: the DAMO bacteria do not need oxygen to grow and therefore the aeration requirements are reduced and, most importantly, because a high air flowrate promotes the stripping of methane.

It can be seen that DAMO archaea were outcompeted by the other microbial groups at every region of operation. In this study we have not focused on the effluent limits (e.g. nitrate, ammonium levels); however, the presence of DAMO archaea can be essential if nitrate levels are to be reduced given that: i) the amount of COD is not enough to denitrify the nitrate produced by the NOB and ii) operating at high TSS promotes the presence of anammox bacteria, which produce a small amount of nitrate during nitrogen removal.

As the minimum level of oxygen is 0.8 mg/L in order to ensure mixing and suspension of the biomass, pure anaerobic/anoxic environments are not reached. However, this reactor configuration has also been implemented with biomass supports in the anoxic chambers, which would allow the development of biofilms. Such biofilms would provide a pure anoxic environment and allow a better stratification of the microbial groups. Additionally, it would allow operating at a higher TSS, thereby maximizing the activity of the slowly growing bacteria.

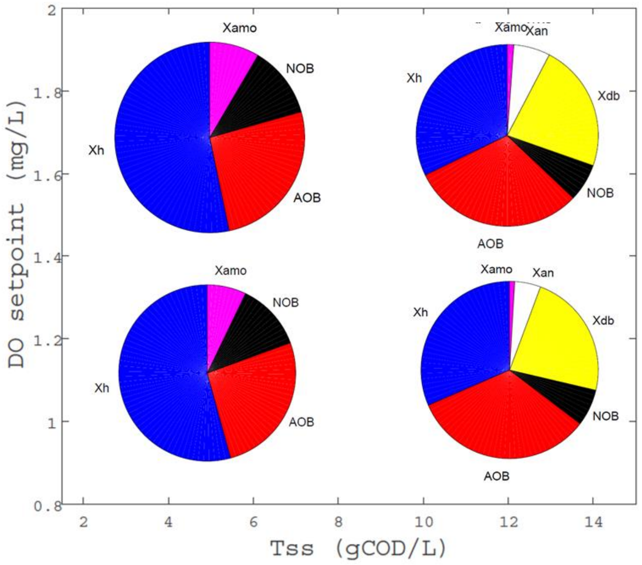

Fig. 6. Microbial populations in the anoxic chamber at different regions of operation w.r.t. the level of dissolved oxygen and total solids in the aerobic chamber.

4. PLANT OPERATION W.R.T. OBJECTIVES

From Fig. 5, it can be concluded that it is convenient to operate at conditions DO = 0.8 mg/L and TSS = 13 gCOD/L. This point would be the optimal for the objective defined in eq. 10 but it is not necessarily the optimal; it depends on the objective defined. For instance, different objectives can be defined as follows:

i) If the plant were to discharge into groundwater or a sensitive water body, maximizing nitrogen removal would be a fair objective (almost regardless of the carbon footprint associated). The operating conditions would be DO 0.8 mg/L and TSS 13 gCOD/L which in this case are coincident with the previously mentioned.

ii) If the plant treats a sidestream that would then be subjected to nutrient removal, the nitrogen removal becomes less important as other parts of the plant would tackle it. Operating at low TSS and high DO would allow minimising the carbon footprint by using the AMO bacteria to remove a significant part of the methane. However, note that the relative weight between the methane and electricity on the carbon footprint impact depends on the electricity mix of the region.

iii) If the plant was located in a region with a mix that is dominated by renewable electricity, minimizing the carbon footprint would be equivalent to minimizing the methane release. Operating at conditions where the DAMO bacteria thrive would fulfil these objectives (high TSS)

5. CONCLUSIONS AND FUTURE PERSPECTIVES

A thorough model-based analysis of the operation of a complex (7 microbial groups) provided insight about the impact of the operating conditions on the performance of the plant. It was seen that the definition of different performance index allowed visualizing the necessary trade-offs to operate the plant and how the operation depends on the defined objectives. Further work on this area will include transferring the conclusions drawn from the operating maps to a plantwide control structure and its implementation at pilot scale.

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