Model-based methodology for the design of optimal control strategies in MBR plants.

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Abstract
This paper proposes a model-based methodology that allows synthesizing the most appropriate strategies for optimising the operation of wastewater treatment plants. The methodology is applied with the aim of maximising the nitrogen removal in membrane bioreactors. The proposed procedure is based on a systematic approach composed by four steps. First, a sensitivity analysis of the input variables is carried out in order to obtain a first assessment of the potential for operational improvements. Then, the optimum input variables values are calculated by a model-based optimisation algorithm that minimises a cost function associated with the effluent total nitrogen at different temperatures. Then, the optimum operational strategies are identified. Finally, these operational strategies are the conceptual knowledge base for designing automatic control laws. The obtained optimal control strategies have shown a significant improvement of performance in comparison with a fixed operation for the studied case, decreasing the total nitrogen by 40%.

Keywords: optimisation; WWTP; operation; model-based; MBR.

INTRODUCTION

Nowadays, the use of mathematical models and simulations of wastewater treatment plants have become very important for optimising their design and operation. In the last decades, several models that dynamically describe the biochemical transformations taken place in the biological processes have been developed (Henze *et al.*, 2000). One of the main advantages of mathematical modelling and computer simulation is the capacity to analyse many different scenarios with very little effort. This is a critical property for optimisation algorithms since a lot of simulations need to be carried out in order to locate the optimal solution and, in real life, this would be unfeasible in terms of time and budget.

Furthermore, wastewater treatment plants (WWTPs) are commonly designed for critical conditions but they are working at under loaded conditions most of the time, offering a great opportunity for optimizing their operation. All the possible combinations of the input variables (wastage flow, dissolved oxygen set-point, etc.) define the feasible operating space of the plant. However, some of the points within the feasible region do not comply with the process requirements; thereby these operational points should be avoided. Hence, the allowable operating zone is a subspace of the feasible operating space where those points are not included. Although all the points within the allowable operating zone are suitable for operating the plant, each of them can produce different outputs in terms of consumed energy or effluent quality. Hereby, by properly selecting the operating point of the MBR plants, its performance can be optimised. However, since the state of the MBR plants is constantly fluctuating due to influent or temperature disturbances, the optimum operating point is also permanently varying. Thus, instead of using a fixed optimal operating point, a set of generic control laws for constantly optimising the plant performance is proposed. These control laws will be synthesised using several model-based optimisations at different plant temperatures.

The optimal operation of the conventional activated sludge (CAS) plants has been widely studied (Galarza *et al.*, 2001) but the implementation of the new membrane bioreactor (MBR) technology has introduced several differences with the CAS technology. On the one hand, the MBR can be operated at higher total suspended solids (TSS) concentrations, which leads to a better biological performance and filtration. On the other hand, the distribution of the solids is also very different since in the MBR technology there is a significant gradient of solids between the MBR and the rest of the tanks (Beltrán *et al.*, 2009). Additionally, MBRs are operated at a constant air scour flow rate, which is normally not lowered because of membrane fouling potential (Judd and Judd, 2011). All these factors can affect the performance of the process and, therefore, the operational strategies that are commonly applied for CAS plants should be revised when membrane reactors are incorporated. Nopens *et al.* (2007) studied the optimisation of the biological performance of a side stream MBR. Verrecht *et al.* (2010) proposed a model-based optimisation of a small-scale decentralized MBR for enhancing energy savings and biological efficiency. Lim *et al.* (2011) optimise the operational conditions of an MBR for maximising the COD and nitrogen removal. Dalmau et al. (2013) carried a model-based study of the integrated operation of a nutrient removal pilot scale MBR. Mannina and Cosenza (2013) present an integrated mathematical model for minimising energy costs. Gabarrón *et. al* (2015) propose a mechanistic model for reducing the aeration energy costs. However, all these studies share a common limitation, they lack control laws for optimising the plant performance despite operational disturbances.

Thus, this paper proposes a model-based systematic methodology for synthesizing control strategies for optimising the operation of MBRs. This methodology has been applied for maximizing nitrogen removal in MBR plants.

METHODS

Model-based construction of control laws

The proposed procedure for the synthesis of operational strategies and controllers in MBR plants is based on a systematic approach composed by four consecutive steps:

Simulation-based exploration of the operating scenario. This first step of the procedure aims at assessing the effect of manipulating the input variables, by changing the influent load and the temperature, in the final process performance. Simulation results can be normally condensed in sensitivity plots or nomograms to facilitate their interpretation. If simulations suggest that an adequate manipulation of input variables offers a significant potential for improving process efficiency at different scenarios, the next step can be launched.

Model-based calculation of the optimum operating points. This second step proposes the application of model-based mathematical optimization algorithms for the automatic calculation of the most appropriate sets of manipulated variables in all the scenarios under study. Each optimization problem requires the definition of the degrees of freedom (typically the free manipulated variables), the restrictions (requirements or boundaries) and the cost function (normally associated to effluent quality or economical costs). A complete description of the optimization algorithm can be found in Rivas *et al*. (2008).

The result of this step is the set of optimum operational points for the predefined operational objectives and restrictions.

Identification of the optimum operational strategies. For this purpose, the trajectories of both the optimum operational points and the state of the process should be related, to identify the criteria for optimizing process performance under changing scenarios. These criteria can be qualitative or quantitative and they are normally associated with rules or properties that are met by most of the optimum points under changing conditions and, consequently, they are not significantly affected by process perturbations.

Design and model-based validation of the automatic controllers. This final step consists of transforming (when possible) these optimum operational rules to automatic control loops, capable of selecting the most appropriate value of the manipulated variables at each moment using the information provided by the available measurement data. A final model-based validation should be carried out in order to confirm or refute the initial expectations in process improvements.

Description of the case study: MBR for N removal

The proposed model-based procedure for designing operational strategies has been applied to construct and validate the most appropriate automatic controllers for maximizing N removal in MBR reactors. The following virtual plant will be used for this paper.

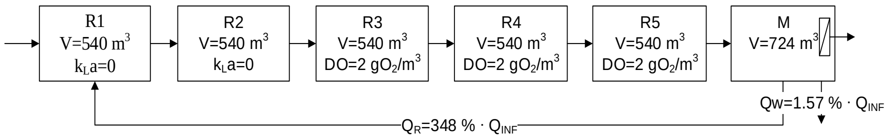

Figure 1. Plant layout, dimensions and operational variables for design conditions at 13ºC

Figure 1 shows the predenitrification-nitrification MBR plant layout used as case-study, which is one of the most common configurations for nitrogen removal. The MBR plant is composed of five tanks: the first two tanks are in anoxic conditions (without external aeration) for denitrification and the other three will remain in aerobic conditions for the nitrification process. Nitrates produced in the aerobic tanks are sent to the anoxic tanks by the recirculation flow $Q_{R,}$ and the total solids of the system are controlled by the wastage flow Q_W. The final MBR tank is operated at a minimum constant aeration flow, calculated to prevent an unsuitable fouling of the membrane using the membrane manufacturer recommendations. ASM2d has been used for the biological transformations at the reactors. Since this paper is focused in the biological performance of the MBRs the membrane fouling has not been taken into account. Characteristics of influent load are presented in Table 1.

Table 1 Characterisation of the influent wastewater

Q_{INF} ($m^3 \cdot d^{-1}$)	19400	S_{NH4} (g N·m^{-3})	24.2	X_H (g COD·m^{-3})	31.3
S_I (g COD·m^{-3})	27.3	S_{ALK} (mol HCO_3^-·m^{-3})	7.0	X_{TSS} (g TSS·m^{-3})	232.8
S_F (g COD·m^{-3})	68.8	X_I (g COD·m^{-3})	56.2		
S_{PO} (g P·m^{-3})	4.6	X_S (g COD·m^{-3})	222.9		

Table 2 Plant design optimisation problem

Objective function	Minimal total volume	
Variables	V; Q_R; Q_w	
Constraints	$Q_R <= 8 \cdot Q_{INF}$	$TSS_{MBR} \leq 10000$ g $TSS \cdot m^{-3}$
	$NH_{4,effl} \leq 1$ g $N \cdot m^{-3}$	$NO_{effl} \leq 8$ g $N \cdot m^{-3}$

The minimum volume of the MBR tank has been estimated using commercial information from membrane manufacturers. The optimum dimensions of the other five plant reactors have been automatically calculated looking for the minimum volume of the plant that is able to fulfil the required effluent requirements at critical conditions (13ºC) (Table **2**) (Rivas *et al*., 2008). The restriction of assuming similar volume for each reactor has not a significant effect in the results. Other possible plant layouts, like the BSM-MBR (Maere *et al*., 2011), have been also analysed but they don’t show a significant improvement of process performance.

RESULTS

Simulation-based exploration of the operating scenario

A simulation-based analysis has been carried out with the aim of assessing the effect of the main input variables (recirculation ratio and dissolved oxygen) to N-NH_4 effluent concentration and total effluent nitrogen concentration (considered simply as the sum of N-NH_4 and N-NO_3 concentrations). The recirculation ratio (Q_R / Q_{INF}) has been changed between 1 and 8 (being 8 the upper limit of the pump) with a 0.1 step size and the dissolved oxygen concentration in the aerobic tanks has been operated in the 0.0-2.0 g $O_2 \cdot m^{-3}$ range with a 0.1 g $O_2 \cdot m^{-3}$ step size. This way the potential for improvement of the plant performance can be assessed. Moreover, it is very important to study the shape of the feasible operating space so that very sensitive optimum zones can be avoided to assure the stability of the WWTP.

Figure 2 shows the total nitrogen concentration isolines in continued lines while the ammonium concentration isolines are represented by dotted lines, both variables are shown in gN / m^3. Two different temperatures are presented: 15 ºC and 21 ºC.

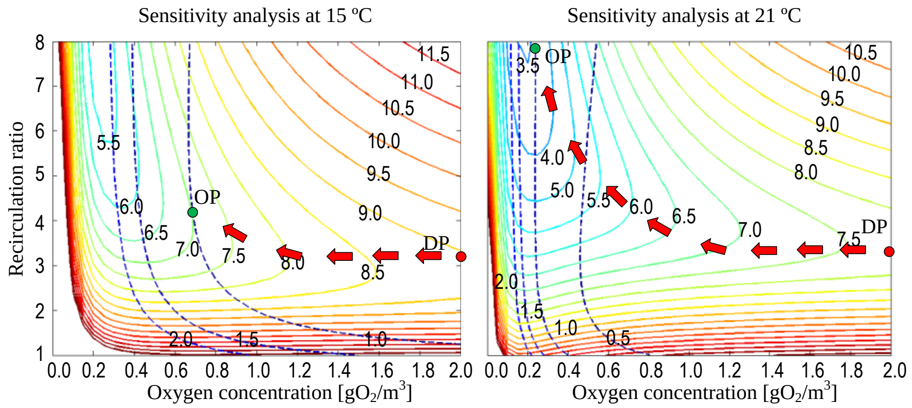

Figure 2 Total nitrogen and ammonium concentration isolines at different temperatures

First at all, it can be observed that the temperature does not affect significantly the qualitative effect of the operational variables. Besides, the ammonium concentration decreases when the oxygen in the aerobic tanks R4 and R5 is increased, as expected.

Moreover, the ammonium can be reduced by the increase of the recirculation rate. Furthermore, the total nitrogen first decreases with the oxygen and then starts to increase, due to the equilibrium between the eliminated ammonium and the produced nitrates. Finally, the total nitrogen at first decreases when the recirculation rate is increased but there is a limit from which the total nitrogen begins to increase. This behaviour is mainly caused by the equilibrium between increasing solids concentrations in the reactors and sending higher oxygen to the anoxic tanks.

Finally the design point (DP) and the optimal point (OP) have been represented. The design point is the value of the input variables at the design temperature (13 ºC) while the optimal point is the operational point that, maintaining the volume distributions, minimizes the total nitrogen concentration of the effluent and meets the ammonium concentration constraint at the temperatures under study (15ºC and 21ºC in the examples). The red arrows represent how the optimal operational point has shifted with the temperature changes. It can be seen that, in both cases, the lowest effluent total nitrogen is achieved at low oxygen set points and high recirculation ratios. However, the restriction of the effluent ammonia (1 gN / m^3) prevents from operating in that zone.

It is interesting to note that the total amount of nitrogen could be theoretically reduced by a 22 % and a 51 % at 15 ºC and 21 ºC respectively. Hence, the performance of the plant has the potential to be greatly enhanced by an optimal operational strategy. Moreover, it can be seen that the operating space is smooth and continuous. Thereby, small disturbances will have little impact in the optimal point. This facilitates the design of optimal controllers.

Once it has been seen that there is room for optimising the plant operation, the next step is to calculate the optimal operational points.

Model-based calculation of the optimum operating points

The main purpose of this section is to optimise the input variables of the plant at different temperatures and based on these optimisations generic control laws will be synthesised. For this purpose, the first step is the calculation of the optimal values of the operational variables at different temperatures (between 13 ºC and 23 ºC) that minimize the total effluent nitrogen satisfying the constraints. Table 3 summarizes the optimisation problem solved at each temperature.

Table 3 Definition of the optimisation problem for each temperature

Objective function	Minimal total nitrogen in the effluent ($NH_{4,effl}$ +$NO_{3,effl}$)
Variables	DO_{R3}; DO_{R4}; DO_{R5}; Q_R; Q_w
Constraints	$DO_{R3} \leq 2$ g $O_2 \cdot m^{-3}$ $DO_{R4} \leq 2$ g $O_2 \cdot m^{-3}$ $DO_{R5} \leq 2$ g $O_2 \cdot m^{-3}$ $DO_{R4} = DO_{R5}$ $Q_R <= 8 \cdot Q_{INF}$ $TSS_{MBR} \leq 10$ g$\cdot L^{-1}$ $NH^+_{4,effl} \leq 1$ g $N \cdot m^{-3}$ $NO^-_{3effl} \leq 8$ g $N \cdot m^{-3}$

Previous optimisations (not shown) have demonstrated that the evolution of optimum dissolved oxygen at both reactors R4 and R5 is nearly similar. Therefore, for simplicity purposes, R4 and R5 are forced to have the same dissolved oxygen concentration. This additional constraint has reduced the degrees of freedom of the problem, facilitating the further selection of the operational strategy.

The results of the optimisation problem at different temperatures are shown in Figure 3.

The upper figure (A) shows the evolution of the optimal input variables (dissolved oxygen and recirculation ratio) while the lower (B) presents the effluent concentration (nitrates and ammonium) obtained by the corresponding operating point at each temperature.

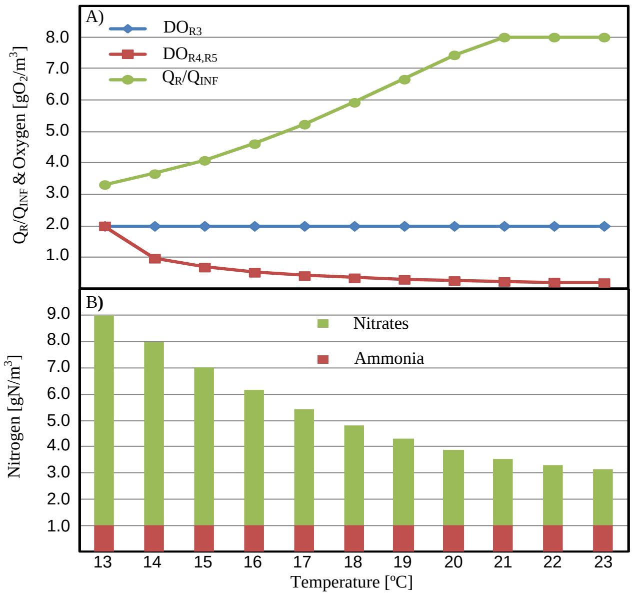

Figure 3 Optimal variables and evolution of the minimal total nitrogen

It has been commonly observed that, for under loaded conditions, the reduction of dissolved oxygen in the aerated reactors reduces significantly the total effluent nitrogen due to the enhanced denitrification (Dalmau et al., 2014). In the MBR plant under study, there are two oxygen related input variables: DO_{R3} and DO_{R4}-DO_{R5}. The reduction of DO_{R3} will lead to a predenitrification-nitrification configuration (DN) while decreasing DO_{R4}-DO_{R5} will lead to a two in-series DN configuration (DNDN). Optimisation results have clearly shown that this second option is most appropriate for optimising the plant under higher temperatures. The first anoxic zone (R1 and R2) is in charge of reducing the recirculated nitrates using influent COD and the second anoxic zone (R4 and R5) carries out a second denitrification process reducing the nitrates produced in R3. Figure 4 shows the resulting evolution of the optimum plant layout when the wastewater passes from cold temperatures to warm temperatures.

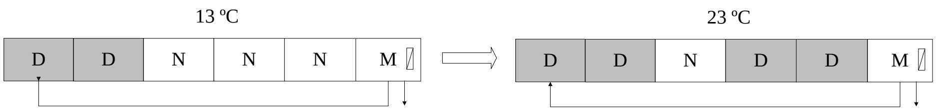

Figure 4 Evolution of the optimum MBR plant layout for increasing temperature

Figure 3 (A) has also shown that optimum recirculation ratio increases with temperature until its maximum value is reached. This raise produces higher nitrates recirculation flux (that compensates the reduction in nitrates concentration), higher suspended solids in the plant (because the maximum concentration of 10,000 g TSS·m^{-3} in the MBR tanks has been maintained) and higher introduction of dissolved oxygen in the anoxic zones. The optimal recirculation flow will result from a balance between them and, since the two first positive effects are reinforced with the temperature, the optimum Q_R value increases along with it.

Figure 3 (B) shows the minimal total effluent nitrogen that can be reached by the plant at different temperatures between 13 °C and 23 °C. It can be seen that the optimum

ammonium concentration remains always constant at its maximum value of 1.0 g $N\cdot m^{-3}$, while the nitrates are progressively reduced up to 2.1 g $N\cdot m^{-3}$ making possible a total effluent nitrogen concentration of 3.1 g $N\cdot m^{-3}$.
These results confirm the great potential for optimizing the operation of the plant to achieve the minimum effluent total nitrogen.

Identification of the optimum operational strategies

Once the evolution of the optimal values of input variables has been analysed, the next crucial point is the synthesis of an optimum (or sub-optimum) set of operational strategies that could be practically implemented (manually or automatically) in the plants. At this point it is very important to remark that these strategies should be clear, realistic and based on measurable and reliable information. Model simulation results have shown their essential role for analysing the process dynamics and the manipulation effects; however, the resulting operational rules should be generic and independent of the specific model results or predictions.

From the analysis of the results obtained in the model-based optimisation, several rules for optimum operation of this kind of MBR plants with N removal can be extracted:

- Dissolved oxygen in R4-R5 should be adjusted to strictly accomplish the effluent ammonium requirements. This strategy moves the plant to a DNDN plant layout that enhances denitrification and reduces aeration costs. Additionally, it maintains the nitrification activity in the membrane reactor, avoiding over oxygenation in the recirculation ratio to the anoxic zones. It is important to remind that aeration in the membrane reactor cannot be reduced to prevent membrane fouling.

- Recirculation ratio should compensate the variations in effluent nitrate concentration. For increasing temperatures (or reducing loads) recirculation flow should be progressively increased in order to supply the nitrates required for denitrification in R1 and R2.

- Sludge wastage rate should be selected with the aim of maintaining (in long-term) the required solids concentration in the membrane reactor. It is interesting to note that this concentration is also perturbed by the variations in the recirculation ratio.

The next step of the procedure is to design the controllers to apply the synthesised optimal control laws.

Design and model-based validation of the automatic controllers

The goal of this section is to design an automatic controller so that a plant can be optimally operated at any temperature despite disturbances. First, the design of the optimum controllers is explained and then, different tests of the controllers have been carried out.

As it has been shown in Table 3, five input variables are considered. However, from the optimisation results, it can be seen that the optimal DO concentration of the aerobic tank R3 does not change with the temperature so this variable does not need to be controlled. For simplicity reasons, the DO concentration in the aerobic reactors R4 and R5 are considered to be the same so they will share the same controller. It has been checked via optimisations that this hypothesis has very little effect on the total effluent nitrogen.

Consequently, just three controllers will be analysed: a DO controller C1, a recirculation flow controller C2 and a wastage flow controller C3. Table 4 shows the controlled variables, their set-points, the input variables and their constraints.

Table 4 Description of the automatic controllers

Control name	C1	C2	C3
Controlled variable	$NH_{4,effl}$	$NO_{3,R2}$	TSS_{MBR}
Set point	1 g $N \cdot m^{-3}$	0.5 g $N \cdot m^{-3}$	10000 g $TSS \cdot m^{-3}$
Control action	DO_{R4-R5}	Q_R	Q_w
Minimum	0 g $O_2 \cdot m^{-3}$	$3.4 \cdot Q_{INF}$	0 $m^3 \cdot s^{-1}$
Maximum	2 g $O_2 \cdot m^{-3}$	$8 \cdot Q_{INF}$	-

Controller C1 manipulates automatically the common DO set-point in reactors R4-R5 to strictly maintain the required ammonium concentration in the effluent (1.0 g $N \cdot m^{-3}$ at this example). This control strategy was successfully validated at full-scale plants (Ayesa et al., 2006) but, as said before, the specific characteristics of MBR plants tends to move the plant layout to a very efficient DNDN configuration during under loaded conditions.

Controller C2 is a very well-known loop that manipulates the recirculation flow in order to maintain a minimum (but higher than zero) nitrates concentration at the end of the anoxic volume. This loop was successfully validated at full-scale plants (Ayesa et al., 2006). It should be noted that a minimal recirculation rate of 3.4 is used to maintain a minimal biomass concentration.

Controller C3 regulates the long-term amount of solids in the system to guarantee appropriate conditions (suspended solids) for the membranes filtration. It is interesting to remark that this loop should have a slow dynamic decoupled from possible fast perturbations in the solids distributions among tanks.

Three incremental PI controllers (Åström and Hägglund, 1995) have been programmed and tuned in order to carry out a first assessment of the control strategy under dynamic conditions. For testing these controllers a one year influent with variations in the temperature based on the BSM1_LT (Rosen et al., 2004) has been used.

Table 5 shows the average results for different control strategies that combine the simultaneous switching-on of different control loops. Strategy A consist of operating the plant at the fixed operational point selected for design at critical conditions (DP in Figure 2). Strategies B, C and D show the effect of incorporating different loops and, finally, Strategy E combines simultaneously the three loops. It can be clearly seen that C1, the dissolved oxygen control, is the most important controller in the plant since its activation is the crucial factor for decreasing the total nitrogen in the effluent.

Table 5 Average results for different control strategies

Strategy	C1	C2	C3	TSS_{MBR} (g $TSS \cdot m^{-3}$)	$NH_{4,effl}$ (g $N \cdot m^{-3}$)	$NO_{3,effl}$ (g $N \cdot m^{-3}$)
A	OFF	OFF	OFF	9765	0.4	7.6
B	OFF	OFF	ON	9961	0.4	7.5
C	ON	OFF	ON	9983	1.0	4.5
D	ON	ON	ON	9981	0.4	6.7
E	ON	ON	ON	9976	1.0	4.2

Figure 5 shows the evolution of the 24 h-average ammonium and nitrate concentrations throughout the dynamic simulation of control strategies A and D. The dark grey line is associated to the closed loop strategy D while the light grey line represents strategy A. The ammonia and nitrates concentrations are shown in the upper half of the graph and the oxygen set point is represented in the lower half. It can be clearly seen how the denitrification of the controlled plant can be greatly enhanced by the automatic controllers, decreasing the total nitrogen by 40%. It is expected that these very successful results can be improved additionally using more sophisticated controllers (for example incorporating mobile-averaged windows and predictive actions) but this is part of the current research activity of the research team.

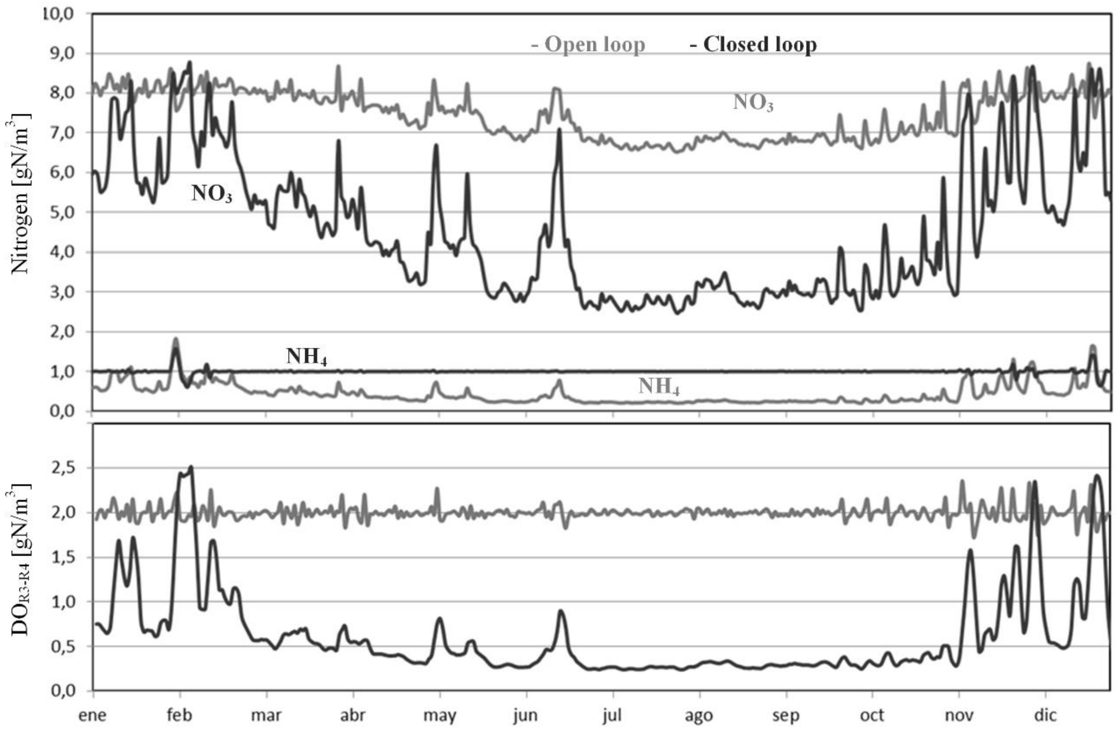

Figure 5 N-NH_4, N NO_3 effluent concentrations for open loop and closed loop strategies (up). DO_{R4-R5} trend for open loop and closed loop strategies (down)

CONCLUSIONS

The operational optimisation of MBRs is a complex task due to the high amount of variables involved in the biological processes and the continuous disturbances in the influent and temperature. This paper has presented a model-based systematic procedure for analysing the influence of input variables in process performance and the use of automatic model-based optimisation algorithms for designing the most appropriate operational strategies.

The proposed procedure has been applied to synthesize reasonable control strategies for a case study MBR plant. The optimisation results have identified the most suitable strategies for minimising effluent nitrogen in MBRs, which incorporates some remarkable differences from the rules and criteria conventionally used in predenitrification-nitrification plants. It is particularly noticeable the automatic modification of plant layout from DN trough DNDN configuration for optimising nitrogen removal at high temperatures. Finally, the performance of the proposed controllers has been successfully validated by long-term simulations.

Current research activity is focused on using the designed methodology to improve the operational strategies in a full-scale MBR system.

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