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Upgrading a decision support system for air-scour control in flat sheet membrane bioreactors

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Abstract: A decision support system to reduce energy consumption has been validated during five months in a flat sheet membrane bioreactor pilot plant treating urban wastewater. Membrane bioreactor technology consists of biological nutrient removal combined with physical separation using microfiltration or ultrafiltration membranes for wastewater treatment. The main operational cost in membrane bioreactors is the energy consumed by the blowers to reduce the fouling phenomenon. The paper demonstrates the benefits of the performance of the intelligent decision support system for air-scour control, in terms of energy reduction through the evolution of the fouling. Overall, the intelligent decision support system saves 25% of the air consumed, which may represent a savings of as much as 56% in terms of power consumption. However, based on the evaluation of the validation results, this control system has been upgraded to avoid any plant shutdown or data saving failure.

***Keywords**:* automatic control; intelligent decision support system; membrane bioreactor; air-scour; wastewater.

1 INTRODUCTION

Decision support systems (DSS) have successfully improved the management of conventional activated sludge (CAS) systems in wastewater treatment plants (WWTPs), as stated by Rodríguez-Roda et al. [2002], Comas et al. [2003], Martínez et al. [2006a] and Martínez et al. [2006b].

CAS systems are being replaced with new technologies that can improve process performance and water quality. The implementation of membrane bioreactor (MBR) technology in the field of wastewater treatment has recently increased due to its superior effluent quality as compared to CAS systems. Besides MBRs are more compact because secondary settlers and tertiary treatment are replaced by membrane filtration, as mentioned in Judd [2011]. However, the main limitation of MBR technology is membrane fouling, which causes a decrease in permeability and, consequently, high energy consumption due to the air-scour system used for physical cleaning (Judd, [2011]). Hribljan [2007] shows that the power used in air-scour can be 30% of the total energy consumption of the plant. While CAS systems consume approximately 0.5 $kWh \cdot m^{-3}$, recent studies carried out by Palmowski et al.

[2011] defined an energy consumption ranging from 0.7 to 1.8 kWh·m^{-3} in MBRs used for municipal wastewater applications.

Accurate mathematical models predicting fouling behaviour as a function of air-scour are not available due to a lack of fundamental knowledge between the process variables and the affected processes. However, an intelligent (knowledge-based) DSS for air-scour control, based on expert and empirical knowledge, has been developed in previous studies (Ferrero et al. [2011a]). DSS are multi-level, knowledge-based, computer systems that not only reduce decision-making time, but also improve the consistency and quality of the decisions. According to Poch et al. [2004], DSS are able to deal with complex problems by integrating artificial intelligence (AI) techniques with statistical/numerical methods under a common architecture.

The aim of this paper is twofold: first, to summarize the satisfactory results obtained during the five-month validation period of the IDSS (Intelligent decision support system) for air-scour control in terms of the air-scour saved, and second, to illustrate the corresponding upgrade of the IDSS, including a new knowledge-based supervision module designed to guarantee its robustness.

The paper is organized as follows: first of all, the pilot plant and the IDSS for air-scour control are explained. Secondly, the validation results of the air-scour control system are shown, focusing on air saved. Then, the upgrades carried out in the IDSS to improve its robustness are described. Finally, the last section summarizes the main findings of the present work.

2 MATERIALS AND METHODS

2.1 Flat sheet MBR pilot plant

The IDSS for air-scour control has been validated in a flat sheet (FS) MBR pilot plant treating urban wastewater from the wastewater treatment plant (WWTP) of Castell-Platja d'Aro (Catalonia, NE of Spain). Figure 1 presents a scheme of the pilot plant which is explained in detail by Monclús et al. [2012].

The microfiltration (MF) membranes used have a total membrane area of 8 m^2 (LF10-Kubota). The online measured variables are permeate flow rate, air-scour flow rate, transmembrane pressure (TMP) and mixed liquor suspended solids (MLSS). The air-scour flow rate is modified by a pneumatic valve.

2.2 IDSS architecture and algorithm

The IDSS for air-scour control was first presented by Ferrero et al. [2011b]. The IDSS is based on a three-level architecture (Figure 2a). The lower level acquires and processes the data, the middle one contains the algorithms used to optimize the air-scour consumed, and the higher one activates or deactivates the control level depending on process alarms.

At the first level, TMP and permeate flux (J, in L·m^{-2}·h^{-1} or LMH) data are sampled every 10 seconds and processed to eliminate the outliers or the non representative values for the filtration sequences, such us relaxation phases. Then, the median is calculated for each permeation cycle and values higher and lower than 20% of the median are excluded (Figure 2b). Finally, the average per cycle is calculated and the permeability (in LMH·bar^{-1}) is obtained based on equation (1), both per cycle and per day. Permeability is used instead of TMP because it also considers the flux. Nevertheless, the full scale WWTPs in Catalonia with MBR technology usually work at constant flux as demonstrated by Gabarrón et al. [2011].

$$K = {}^{J}/_{TMP} \qquad (1)$$

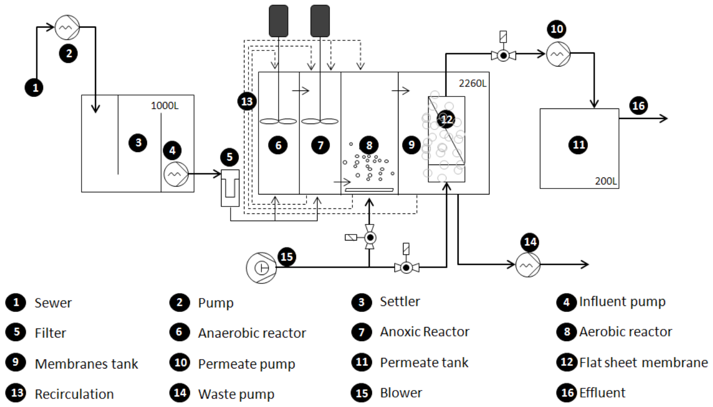

Figure 1. Pilot plant scheme.

Short term or current trend (ST) and long term or reference trend (LT) are calculated as the slope of the daily averaged permeability values for 4 and 14 days, respectively. Finally, the slope ratio (SR) is computed as in equation 2.

$$SR = {}^{ST}/_{LT} \qquad (2)$$

Since we are interested in the tendency of the membrane fouling rate, SR becomes the parameter to be monitored in the logics of the control level.

The control actions (medium level) depend on, basically, the TMP, LT, ST and SR. Table 1 contains all the actions carried out by the control level. If the membranes are very clean (TMP≥-5 mbar), the air flow must be decreased (-0.2 m^3/h). Then, LT determines if membranes are being cleaned (Case A), fouled (Case B) or remain stable in a long term trend (Case C). Finally, ST value determines the possibility of decreasing, increasing or keeping the air-scour flow rate stable. A fuzzy rule-based control built upon Table 1 is currently under study.

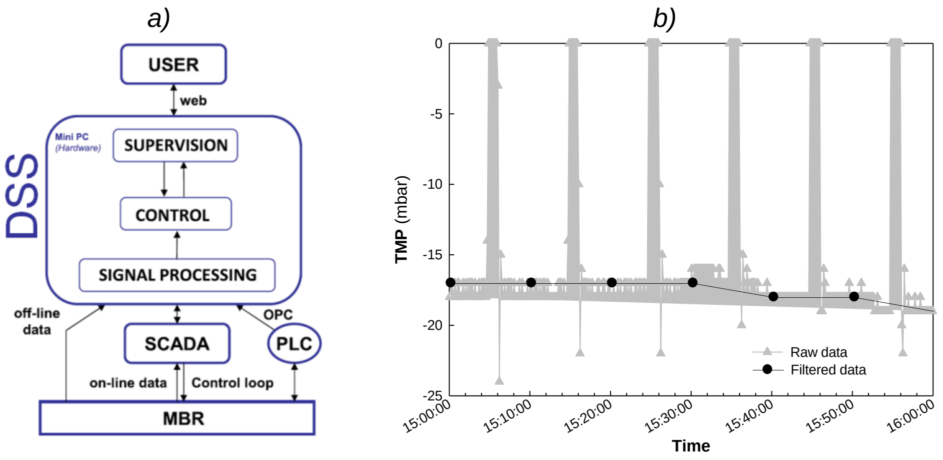

Figure 2. a) Three-level structure of the IDSS, b) Data acquisition and filtering.

Table 1. Control algorithm

Initial condition			**Action (m^3/h)**
TMP ≥ -5 mbar			**-0.2**
TMP < -5 mbar			See cases: A, B, C
Case A: (cleaning)	**slope LT > 0**	**Conditions**	**Action (m^3/h)**
		slope ST > 0 & slope ratio ST/LT ≥ 1 (ST ≥ LT)	**-0.4**
		slope ST > 0 & slope ratio ST/LT < 1 (ST < LT)	**-0.2**
		slope ST ≤ 0	**0**
Case B: (fouling)	**slope LT < 0**	**Conditions**	**Action (m^3/h)**
		slope ratio ST/LT < 0 (ST > 0)	**-0.2**
		slope ratio ST/LT > 0 (ST < 0)	See points: 1…8
		***1**: slope ratio ST/LT = [0, 0.3)*	**-0.3**
		***2**: slope ratio ST/LT = [0.3, 0.6)*	**-0.2**
		***3**: slope ratio ST/LT = [0.6, 0.9)*	**-0.1**
		***4**: slope ratio ST/LT = [0.9, 1.1)*	**0**
		***5**: slope ratio ST/LT = [1.1, 1.4)*	**0.1**
		***6**: slope ratio ST/LT = [1.4, 1.7)*	**0.2**
		***7**: slope ratio ST/LT = [1.7, 2)*	**0.3**
		***8**: slope ratio ST/LT ≥2*	**0.4**
Case C	**slope LT = 0**	**Conditions**	**Action (m^3/h)**
		slope ST < 0	**0.1**
		slope ST = 0	**0**
		slope ST > 0	**-0.1**

3 RESULTS

3.1 Validation of the IDSS in a flat sheet MBR pilot plant

FS membranes were operated under constant flux (21 LMH) during five months without a high decrease in TMP (Figure 3). Daily permeability as well as moving ST and LT values were calculated. Control action was taken once a day, according to the rules shown in Table 1. This variation in air-scour was soft to avoid sudden fouling episodes.

Before the IDSS was implemented, the pilot plant was operated with an air flow rate of 11 $m^3 \cdot h^{-1}$, as stated by the manufacturer, Kubota. Hence, this value is taken as a reference to calculate the air-scour savings, illustrated in Figure 3. The minimum air flow rate reached was 6.25 $m^3 \cdot h^{-1}$ while the average was 8.25 $m^3 \cdot h^{-1}$. The mean air-scour savings was 25%, which may represent an energy savings of 55.8% using centrifugal blowers. In most cases the MLSS was higher than 5 $g \cdot L^{-1}$, which is the recommended value needed to obtain a well-scoured membrane surface in FS technology. The biological nutrient removal (BNR) processes were not affected during the validation time, fulfilling the discharge limit imposed by DE91/271/CEE and achieving high efficiencies, comparable to the work done by Monclús et al. [2011].

During the first 30 days the TMP was very low and the control system decreased the air-scour without considering LT or ST. However, there was a problem with the permeability calculation, because these values were 0. When the TMP reached values lower than -5 mbar, the permeability was well computed. Another problem appeared during plant shutdowns (days 36, 41, 42, 58, 82, 83, 97, 123, 128, 129 and 130). On those days, the values of TMP, MLSS and permeability were not registered, thus the control system considered them to be 0. The control action obtained with these values might be different from the one provided by well calculated permeability. The improvements that will be presented in the next section aim to solve these problems and to improve the robustness of the entire IDSS.

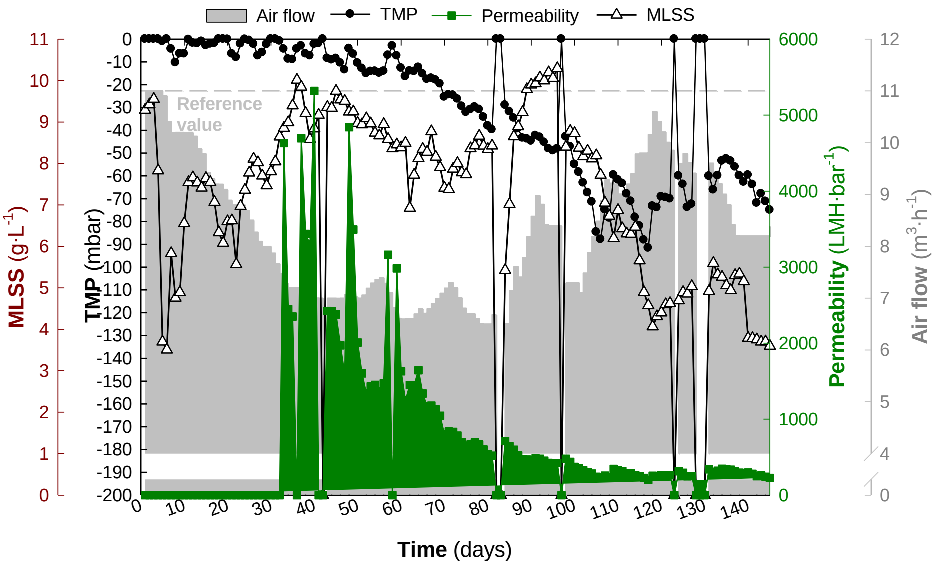

Figure 3. Results of the IDSS for air-scour control validation.

Although the IDSS for air-scour control was validated during five months with successful results, the data acquisition, processing and control algorithms should be upgraded to obtain a more robust IDSS, able to be implemented in any full-scale WWTP.

3.2 Upgrades in the IDSS

In order to improve the robustness of the IDSS for air-scour control several experience-based improvements have been made to:

- Refine data acquisition and processing, e.g. after plant shutdowns (signal processing level).
- Ensure robust control actions, e.g. when there are missing data (control level).
- Improve the process supervision for FS membranes, e.g. initialization of the IDSS system after plant shutdowns (supervision level).

Figure 4 summarizes the upgrades carried out in the IDSS in form of a decision tree. Some rules had to be added to the signal processing level (green part of Figure 4), others had to complement the control level (blue rules), while a knowledge-based module was added to supervise the air-scour control in flat sheet membranes (red parts of Figure 4).

First of all, at the **data processing level** (green rules), TMP and flow rate (Q) are sampled every 10 seconds (raw data filtering module). The median filtration mentioned previously is applied and average permeability per day (K_d) is obtained. The next (and new) step is to evaluate the permeability value (new permeability evaluation module). The permeability of the previous day is checked. If the data were acquired successfully on the previous day and the actual value is not equal to 0, ST, LT and SR are calculated. If data acquisition was not successful on the previous day (missing data), the actual day value is checked. If it is other than zero, the interpolation between the actual value (K_d) and the last value available (K_{d-n}) is carried out with a new added algorithm. This solution allows "virtual" values (e.g. Figure 5) to be obtained to calculate LT, ST and SR when some days previously there was a plant shutdown or missing data. In order to avoid very large permeability values when membranes are clean (very low TMP), there is a limitation

($K_{max.}$) based on experiences or literature (Judd, 2011) that depends on the membrane type (in FS membranes it is close to 1500 LMH·bar^{-1}). In all cases, if the actual daily permeability is 0, the program does not register any value.

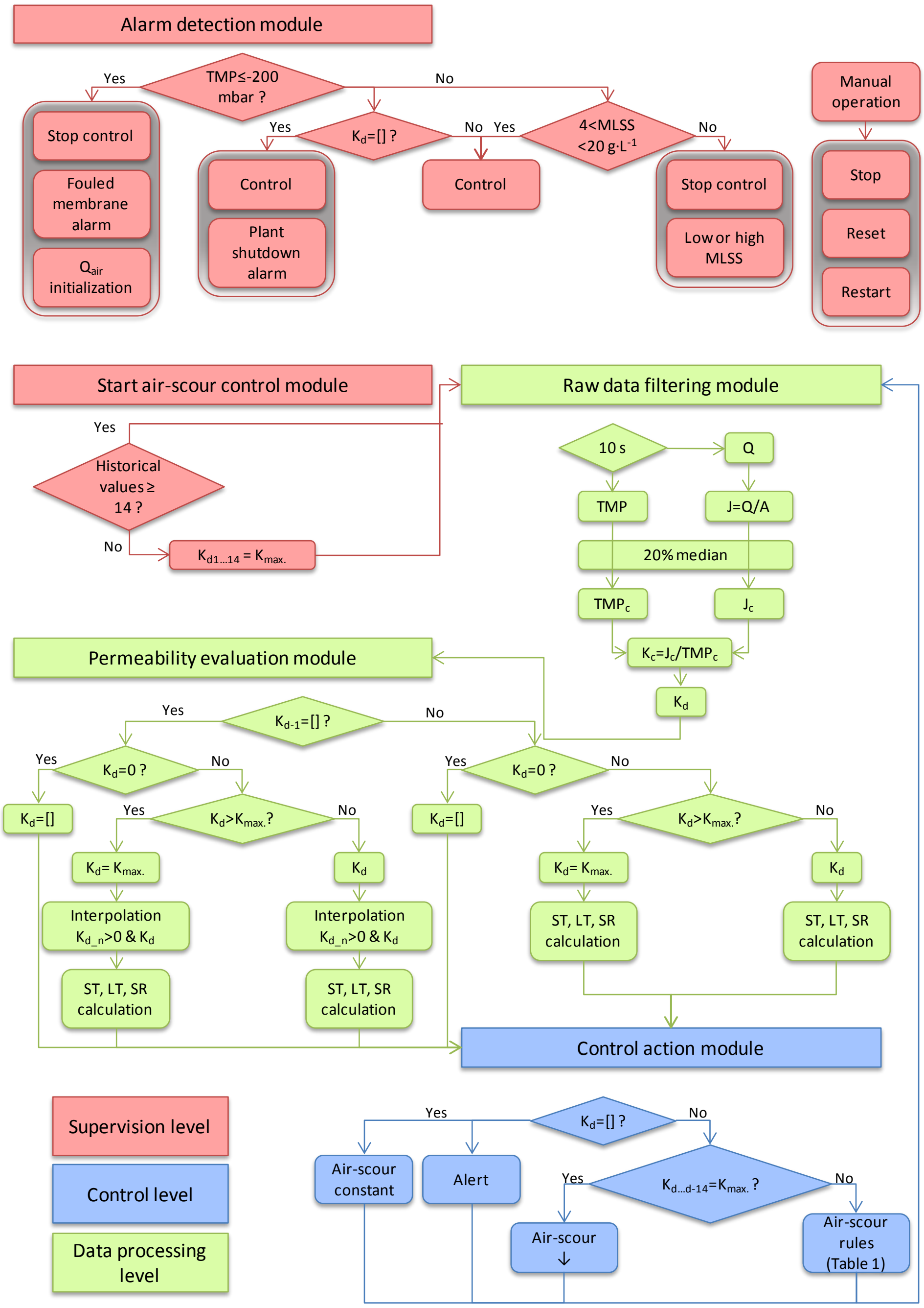

Figure 4. Improvements made in the IDSS through knowledge-based rules.

Secondly, the rules incorporated in the **control level** (blue) ensure that the control actions according to Table 1 are taken once per day, only when data is available and the process is working normally (K_d<$K_{max.}$). If not, the air-scour flow rate is kept constant and an alarm is generated. The new rules also check for very clean membranes (i.e. all 14 of the last values equal to K_{max}), so that the air-scour can be reduced.

Finally, the knowledge-based rules added in the **supervision level** (red) of the IDSS check the proper functioning of the air-scour control in flat sheet MBRs. Specifically, these rules check for completely fouled membranes (based on TMP), for plant shutdowns and inadequate MLSS concentration. If the TMP decreases below the minimum value, a chemical cleaning will be necessary to recover the initial permeability of the membranes. Then, the air-scour must be the maximum and the IDSS has to be restarted. Another value that will be considered with the new module is MLSS concentration because a minimum concentration is needed to ensure a good membrane surface scouring. On the one hand, if the MLSS is between the desired range and K_d is well computed, the air-scour control can be activated. On the other hand, if the MLSS is not appropriate, the air-scour control must be deactivated and the corresponding alarm should be activated, although when it is restarted, the most recent air-scour value has to be maintained. Moreover, this level ensures a minimum of 14 values (start air-scour control module in Figure 4) before any LT calculation is made.

Clearly the control actions using the upgraded IDSS are different (indeed, are better!) than those actions obtained with the old system, where zeros, very high peaks and deep valleys as well as missing data could be present and thus could cause an undesired and incorrect control response (as shown in Figure 5). So now the air-scour control has become more robust.

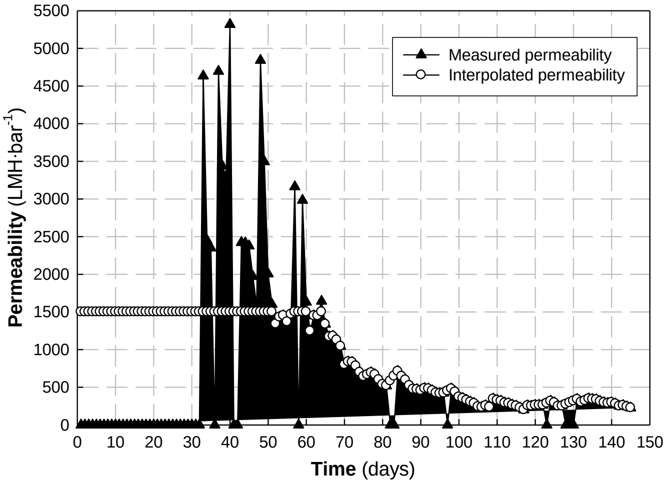

Figure 5. Comparison between measured and interpolated permeability.

4 CONCLUSIONS AND RECOMMENDATIONS

The five-month validation of the IDSS for air-scour control in an MBR has been successful, reducing air consumption by 25% without compromising BNR or leading to faster membrane fouling. The different monitoring parameters were obtained every 10 seconds, filtered and used to obtain the control action in accordance with the long permeability trend, the short permeability trend and different expert rules. Using this primary IDSS the control action taken would be bad if a plant shutdown occurred or permeability values were unusual. The first event is detected when different measured variables equal 0, and the second usually happens when membranes are very clean.

For this, new knowledge-based rules have been explained and justified to obtain the maximum robustness of the IDSS applied in FS membranes. This implies improvement at the signal processing, control and supervisory levels. In addition, with theses modifications, the IDSS has been installed in a full-scale MBR WWTP for validation.

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