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Abstract: Membrane bioreactor technology in wastewater treatment and re-use is currently challenging traditional wastewater methods. However, although this technology presents many advantages as in most membrane filtration processes the permeate flux and permeability declines during filtration due to membrane fouling. Therefore controlling membrane fouling is the key issue in MBR operation. Nevertheless, membrane fouling is a very complicated phenomenon that results from multiple causes. Thus an intelligent Decision Support System for the integrated operation of membrane bioreactors has been developed. This Decision Support System, based on empiric and heuristic knowledge, gathers on-line and off-line information about both the biological and physical processes and integrates artificial intelligence techniques with advanced control algorithms to infer the process performance state before launching the corresponding operation strategy. When the process performance regime is favourable, the decision support system enables to optimise aeration energy while controlling fouling. The aeration control has been successfully validated at pilot scale for saving about 20% of energy and therefore reducing operational costs. Besides, the development of several knowledge-based modules (e.g. start-up or operational problems among others) ensures a robust and complete system adaptable to all kind of membranes while providing higher reliability.

Keywords: Decision Support System (DSS); Expert System; Membrane Bioreactor; Fouling; Automatic control; Permeability.

1. INTRODUCTION

Membrane bioreactor (MBR) technology in wastewater treatment and re-use is currently challenging traditional wastewater methods, due to recent technical innovations and drastic cost reductions of the employed membranes (Fane and Fane, 2005). MBR can be defined as activated sludge systems where the secondary settling has been replaced by a filtration step by using microfiltration or ultra filtration membranes with pores size comprised between 0.01 and 2 μm to produce a very good water quality effluent, free of suspended solids and microorganisms (Poch and Lema, 2008). Membrane filtration in wastewater treatment processes does not need tertiary treatment and reduces significantly the footprint of the biological treatment.

Although the MBR process presents many advantages (higher effluent quality, reduced excess sludge production, drastically enhanced elimination of pathogens and viruses, potential degradation of specific refractory pollutants, higher stability and persistence to shock loads, etc.), as in most membrane filtration processes the permeate flux and

permeability declines during filtration due to membrane fouling (Judd, 2005). The fouling phenomenon, the main operational problem of MBR technology, occurs due to diverse factors (biomass cake formation on the membrane surface, pore reduction due to deposit or precipitation of organic and inorganic compounds and pores obstruction with suspended compound which have similar size than the pores), causing a loss of membrane permeability (permeate flux divided by membrane surface unit and pressure or applied vacuum unit).

Controlling membrane fouling is the key issue in MBR operation. Nevertheless, membrane fouling is a very complicated phenomenon that results from multiple causes. For a given MBR process, the fouling behaviour is directly determined by sludge characteristics and hydrodynamic conditions. Moreover, operating conditions (i.e., SRT, HRT and F/M) and the feed-water composition indirectly affect membrane fouling e.g. by modifying sludge characteristics (Meng et al., 2009). Fouling can be reduced through the influent pre-treatment, treating fluxes at an average flow below the optimized point, carrying out periodical physical cleaning of the membranes (backwashing in hollow fibre membranes or relaxation in flat sheet membranes and air scouring of the membranes with gross bubbles) and chemical cleanings (preventive, maintenance or intensive) (Judd, 2006). Thus membrane fouling results in increased energy consumption for filtration, increased frequency of chemical cleaning requirements and in a reduced overall membrane lifetime. Therefore, the capability to reduce or control membrane fouling, together with energy consumption optimization, will trigger the implementation of high-end MBR treatment systems. Energetic requirements in MBRs suppose approximately a 40% of the total operational costs, from which the main part corresponds to the membrane aeration, and it is one of the major drawbacks in MBR technology implantation.

MBR systems are usually operated with fixed filtration sequences and aeration, generally proposed by membrane suppliers and slightly refined according to operator's experience. This frequently results in sub-optimal performance due to the use of static filtration parameters for dynamic operation. To date simple control approaches aimed to minimize costs end enhance the MBRs filtration efficiency are limited and lack flexibility to cope with variable operational conditions.

This paper presents the development and validation of an intelligent Decision Support System (iDSS) for the integrated operation of MBRs. The iDSS, based on empiric and heuristic knowledge about the process, gathers and integrates on-line information about both the biological (i.e. biomass characteristics) and physical (i.e. sludge filterability) processes to infer MBR state before launching the corresponding operation strategy. This paper illustrates the development of the decision support system, identifying the role of the different modules, and validation results from experimentation carried out in an industrial pilot plant.

2. DEVELOPMENT OF THE iDSS

2.1 Architecture of the intelligent Decision support system

The proposed decision support system supervises in an integrated and remotely way the biological nutrient removal and the membrane filtration process (Comas *et al.,* 2009; Rodriguez-Roda *et al.*, 2009). It is located hierarchically on top of the conventional supervisory control and data acquisition (SCADA) systems, existing in most plants. Figure 1 illustrates the multi-level architecture of the iDSS and the flow of information among the different levels, a lower one responsible of data acquisition and processing, a medium level in which the optimizing control system is located and a higher level that supervises the control module on knowledge basis.
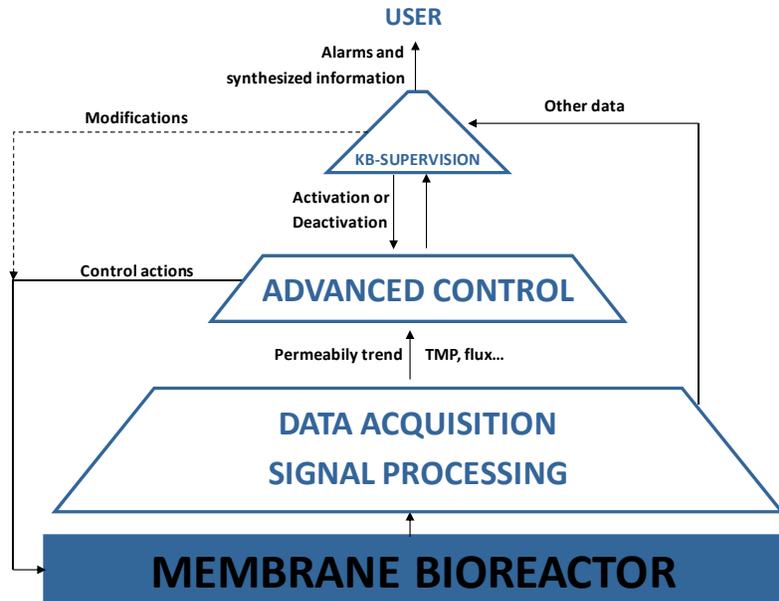
Figure 1. Multilevel structure of the iDSS.

The lowest level of the iDSS is responsible for data gathering and signal processing. It does not only take, filter and validate the on-line data provided by sensors and equipment (e.g. transmembrane pressure (TMP), wastewater flow rates, air flow rate, temperature, dissolved oxygen, etc.) but also integrates additional qualitative and quantitative data provided by the laboratory and/or process operators (e.g. Extracellular Polymeric Substances (EPS), Chemical Oxygen Demand (COD), protozoa biodiversity, sludge viscosity, filterability, mixed liquor suspended solids (MLSS), NO_x^- etc.). The off-line measurements are uploaded daily by the end users. Since the control actions take place once a day at 00.00 on the basis of the automatic signal processing of the on-line data and the following control rules applied, the delay of the off-line measurement is amortised. At the current development stage of the intelligent DSS, the off-line data are employed uniquely in the supervision module in order to activate or deactivate the control modules. The relevant data, once validated, are stored in a dynamic database (MySQL).

2.2 Advanced control module

The medium level governs the automatic control loops of the most important parameters for the biological and physical processes of membrane bioreactors: control of biological aeration, control of permeate and backwashing fluxes and frequencies, control of permeate flux, control of sludge retention time (i.e. waste flow rate), control of sludge and nitrate recycles, etc. This control module of the iDSS includes the necessary knowledge to fix the set points for all these automatic or semi-automatic controllers (e.g. some of them implemented in the SCADA systems as conventional PI or PID), while others are advanced algorithms developed for more advanced controllers (e.g. membrane aeration).

The algorithm for membrane aeration control aims at optimising the aeration energy and is based on the permeability trend. The permeability trend (the slope of the daily averaged values of permeability of the last 4 days) is compared to a reference value (automatically calculated as the moving slope of the daily averaged values of permeability of the last 14 days) and, when the current slope results inferior than the reference value, the air-scour to the membranes can be reduced, and vice-versa (Table 1).

The automatic controller for energy optimisation is only activated when the proces performance regime is diagnosed as 'favorable' by the supervision level i.e. the loss of

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permeability evolves according to standard rates, and no other critical problems, such as malfunctioning, alarms and/or equipment failure affect the process.

Table 1. *Slope rates and control air actions*

Slope rate	Control action	Air control ($m^3 \cdot h^{-1}$)
<0		-0.4
0 - 0.3		-0.3
0.3 - 0.6		-0.2
0.6 - 0.9		-0.1
0.9 - 1.1		0
1.1 - 1.4		0.1
1.4 - 1.7		0.2
1.7 - 2.0		0.3
>2		0.4

The adjustment of control set points (permeability trend, permeate flux, DO, sludge retention time, etc.) can be related to the detection of faults by means of the knowledge-based supervision level. This way the control module ensures an optimal and robust integrated operation of the membrane bioreactors.

2.3 Knowledge-based supervision modules

The use of artificial intelligence tools in the top level provides direct access to knowledge and expertise and makes the iDSS capable of supporting learning and decision making processes. This level consists of a set of knowledge-based modules which become the reasoning core of the iDSS since supervise the control module, as a function of the process operational *mode* (start-up, optimisation, biological problem, biofouling, etc.), to continuously ensure lower operational and energy costs while at the same time maintain or improve effluent quality. All modules are structured at the same level, except for the 'Start-up' module, which will be the only one active during MBR systems start-up, and the 'Saving energy' which can only be launched when no operational problems are detected. The interaction with the end-user is essential in this level, through a remote application with web-oriented graphical and interactive user interface (www.colmatar.es). Next the different knowledge-based modules developed are described.

Start-up module

The start-up module is in charge of monitoring the evolution of the process during the start-up period. It receives all the processed data from the lower level and maintains the design operation strategy while a set of expert rules controls the growth and nature of biomass to reach the optimal level advised by the manufacturer. At the same time, this module regulates the set points of the control loops in order to accelerate the achievement of biological nutrient removal (Figure 2). As stated in the bibliography, a fast mixed liquor suspended solids (MLSS) growth favours the cake layer formation and consequently the permeability stabilization (Judd 2006 ; Di Bella *et al.*, 2006; Le-Clech *et al.* 2006). Thus a 4-level discriminant decision tree has been developed to achieve a high working flux as faster as possible, while at the same time minimizing chemical cleanings. When the process is under *start-up mode*, the control for energy and chemicals optimization is deactivated.
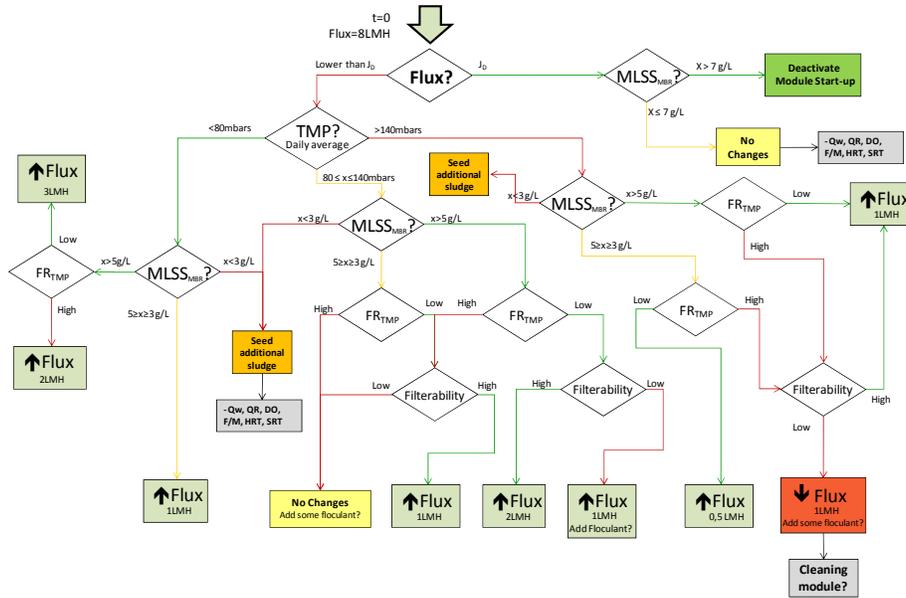
Figure 2. Decision tree for the start-up of MBRs.

Saving energy module

This module includes a set of rules to detect process favourable conditions for aeration energy optimisation. When the permeability is evolving well and no other problems are detected, the advanced aeration controller is active. Then a special plan to monitor the potential adverse effects over the membrane performance is also launched, including corrective (e.g. increase backwash flow rate or duration) and preventive (maintenance and recovery chemical cleanings) control actions or restoring safe mode status in case there is any significant warning. Safe mode is a mode that implies the standard operational conditions suggested by the membrane suppliers.

Biofouling and clogging module

Figure 3 shows the theoretical knowledge-base developed for monitoring and preventing biofouling and clogging problems. Significant changes in TMP (or permeability) are used to infer fouling operational problems. The knowledge base is mainly built upon specialised literature, including empirical and tacit knowledge to relate parameters of biological control (sludge retention time, mass load, dissolved oxygen concentration, temperature, process performance, proliferation of filamentous organisms, etc.) with those relevant for the membrane unit operation (TMP, permeability, extracellular polymeric substances, washing frequency and type, particle size distribution, etc.). A set of heuristic rules can be extracted and used for the inference of fouling problems (e.g. IF EPS concentration increases THEN cake layer formation increases and reversible fouling increases too, which leads to higher values of TMP_1). The adaptation of the knowledge base to each specific MBR system will be carried out through a customization process of the qualitative ranges (high/low, increasing/decreasing, normal/abnormal, etc.) during the iDSS implementation phase
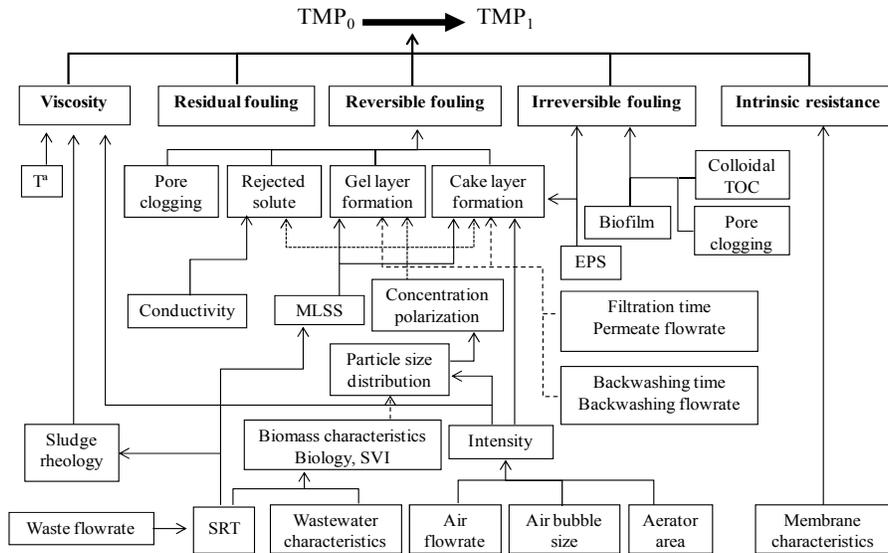
Figure 3. Knowledge Base for the biofouling and clogging operational problems.

Operational problems module

There is a specific module developed and under validation that diagnoses and solves other operational problems. It includes a specific set of rules for the detection of sensors and control loop faults due to mechanical equipment or electrical failures (e.g. damaged or clogged pumps, air system failure) and for typical process faults such as poor performance of the biological nutrient removal process (e.g. lack of nitrification, poor denitrification) and microbiology-related problems (e.g. foaming, deflocculation). The knowledge base included in this module is an evolution of the original knowledge based system developed in our laboratory previously for the activated sludge system (Rodriguez-Roda *et al*., 2002; Martinez *et al.*, 2006).

Other specific modules under development

There are other rule-based modules being developed to account for specific anomalies such as e.g. stand-by of the filtration process of a module or a train during a specified time frame (e.g. due to MBR tank low level), bad sludge filterability, temperature out of range, permeate flux or TMP higher than fixed values. The learning module is also still under development and thus not implemented yet. The objective of the learning module is to register relevant events relative to the biological, filtration and backwashing processes aiming at reusing knowledge gained in accumulated experiences. This module confronts similar situations looking for useful patterns (e.g. comparison of similar patterns of within-cycles TMP and permeability profiles). Case-Based Reasoning is probably the best candidate system to implement the learning module.

3. VALIDATION OF THE iDSS IN PILOT PLANTS

The advanced aeration control of the iDSS has been validated in two different pilot plants. During two years of experimentation, the two pilot plants were operated under different conditions, such as different F/M ratios, recycles, inflows, MLSS concentrations (Monclús *et al.,* 2010a), and with constant or variable permeate flux. Both pilot plants successfully removed C, N and P biologically from raw domestic wastewater (Monclús *et al.*, 2010b). These pilot plants are fully automated with pressure transducers, pH, ORP, dissolved oxygen, ammonium, mixed liquor suspended solids, conductivity and temperature sensors

and have a programmable logic controller and a supervisory control and data acquisition system (SCADA).

The wide range of operational conditions experimented allowed to validate the robustness of the aeration control system on multiple scenarios. It was proven that membrane aeration can be diminished below the minimum (and constant) recommended values for the manufacturer while maintaining an optimal performance throughout the experimental period (high nutrient removal, high permeability values and high filterability). Figure 4 illustrates the membrane aeration provided by the automatic controller as a function of the permeability trend and the energy saving (around 20%) when compared to the constant value suggested by manufacturers.
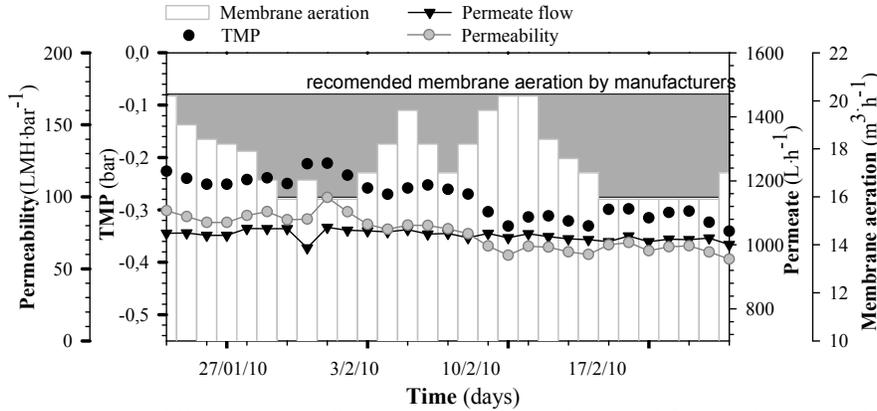
Figure 4. Permeability, permeate flow, TMP and automatic control for membrane aeration. In grey the airflow reduced to save energy.

Additionally, the control system automatically reduces the membrane aeration when a permeate flow is lower than the daily average flow (Figure 5).
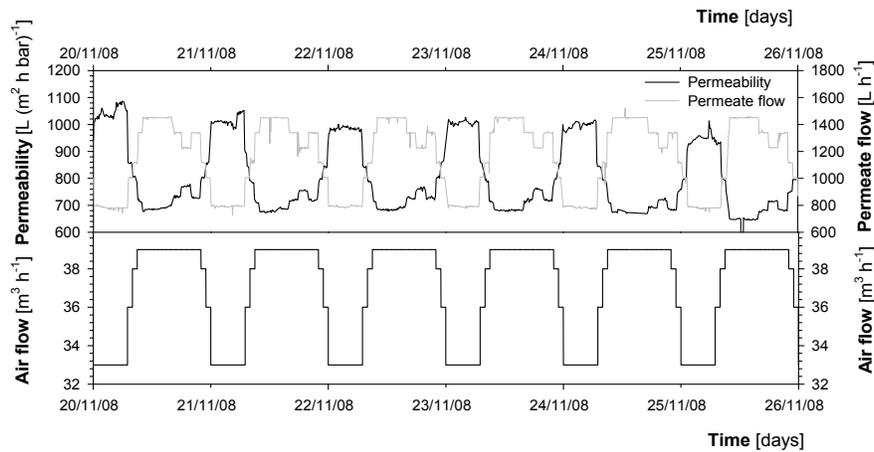
Figure 5. Permeability, permeate flux and airflow rate applied during a process week.

Next investigations will be focused on the development of the remaining knowledge-based modules and the validation of the decision support system in a full scale plant. Performance comparison to other previously published and patented control strategies will also be part of the future prospectives.

4. CONCLUSIONS

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This paper presents the development and partial validation of an intelligent DSS for the integrated operation of membrane bioreactors. The proposed web-based iDSS is based on three-level architecture and integrates advanced control algorithms with knowledge-based techniques. The proposed iDSS has been successfully validated in two different MBR plants for saving energy and therefore reducing operational costs. Besides the development of the start-up, biofouling and operational problems knowledge-based modules among others ensures a robust and complete iDSS adaptable to all kind of membranes while providing higher reliability.

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