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iEMSs 2008: International Congress on Environmental Modelling and Software
Integrating Sciences and Information Technology for Environmental Assessment and Decision Making
4th Biennial Meeting of iEMSs, http://www.iemss.org/iemss2008/index.php?n=Main.Proceedings
M. Sànchez-Marrè, J. Béjar, J. Comas, A. Rizzoli and G. Guariso (Eds.)
International Environmental Modelling and Software Society (iEMSs), 2008

Intelligent Environmental Decision Support System for integrated operation of Membrane Bioreactors

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Abstract: The target of this paper is to present a prototype of Intelligent Environmental Decision Support System (IEDSS) that guarantees robust and independent monitoring and real-time control of membrane bioreactors, and at the same time allows remote supervision of the integrated operation of the biological process and the physical separation by the membranes. The rule-based and model-based systems include empirical and tacit knowledge to relate parameters of biological control to the membrane unit operation. At the same time, the IEDSS is meant to be equipped with an automatic learning module of the membranes life cycle that records and analyses accumulated experiences and allows acquired knowledge to be reused in the future whenever similar situations arise.

Keywords: IEDSS, wastewater, membrane bioreactors, fouling, integrated operation.

1. INTRODUCTION

Membrane bioreactor technology is a fast-development concept that is gaining ground in the field of wastewater treatment, mainly in small facilities that have high quality requirements for water reuse (e.g. [Judd 2005; Lesjean *et al.*, 2004; Cho *et al.*, 2004; Jiang *et al.*, 2004]). Membrane bioreactors offers several advantages over conventional activated sludge plants, e.g. operation at high biomass concentrations, reduced excess sludge production, extremely low suspended solid concentrations in the treated effluent, drastically enhanced elimination of pathogens and viruses, and a superior effluent quality. Furthermore, the high biomass concentration and long sludge retention times in membrane bioreactors positively affects the overall activity of slow growing microorganisms acting in e.g. nitrification or degradation of specific refractory pollutants and lead to a higher stability and persistence to shock loads. Although membrane bioreactors present many advantages, as in most membrane filtration processes, the permeate flux declines during filtration due to membrane fouling [Judd, 2005], which is significantly influenced by the hydrodynamic conditions, membrane type and module configuration and the presence of higher molecular weight compounds, either produced by microbial metabolism or introduced into the process. Controlling membrane fouling is the key issue in membrane bioreactors operation. Nevertheless, general guidelines for the integrated operation and control of membrane bioreactors, which take into account not only type and washing frequency of the membranes, but also the main biological parameters, i.e. especially microbiological imbalances, have not been published yet.

Intelligent Environmental Decision Support Systems (IEDSS) are multi-level, knowledge-based computer systems that not only reduce decision-making time, but also improve the consistency and quality of the decisions. DSS are able to deal with complex problems by integrating AI techniques with statistical/numerical methods under a common architecture [Poch *et al.*, 2004]. IEDSS have demonstrated potential to improve the management of Wastewater Treatment Plants (see for example [R-Roda *et al.*, 1999; Sànchez-Marrè *et al.*, 1999; R-Roda *et al.*, 2001; Rodríguez-Roda *et al.*, 2002; Comas *et al.*, 2001, Comas *et al.*, 2003; Martínez *et al.*, 2006a; Martínez *et al.*, 2006b]).

This paper summarizes and highlights the preliminary results of a demonstration research project. The main objective of the project is to design, develop and implement an IEDSS to control remotely and supervise in real-time the integrated operation of a membrane bioreactor pilot plant for wastewater treatment and reuse. Special emphasis is placed on handling problematic situations whose correct and quick detection minimizes the risk of biofouling. The DSS also establishes a hierarchy in fault detection [Genovesi *et al.*, 2000], distinguishing three main levels: sensor failure (SF), sub-process failure (SPF, for example in control loops) and operational problems (PF, process failure). The main purposes of the IEDSS are:

- to increase operational reliability; for this it is of great importance to integrate the biological process for organic matter and nutrient removal with the physical effect of membrane filtration and backwashing/relaxation,
- to reduce operational and energy costs,
- to maintain or improve the effluent quality for water reuse (higher efficiency),
- to learn automatically and reuse the acquired knowledge.

The paper is organized as follows: First of all, the environmental system under study is described detailing the design and operating characteristics. Then, the architecture and development of the IEDSS, especially the reasoning core (rule-based expert system, model-based system, case-base reasoning system, control algorithms and mathematical model), are described. Finally, some conclusions are drawn.

2. ENVIRONMENTAL SYSTEM UNDER STUDY

The experimental environmental system under study consists of a pilot plant for biological nitrogen removal and tertiary treatment of real wastewater (Figure 1). The pilot plant comprises a pre-screening system, bioreactor (total volume 2260 L) with UCT configuration (anaeobic, anoxic and aerobic tanks) followed by a compartment with hollow fiber membranes (Microza from Asahi Kasei Chemicals Corporation, a total area of 12 m^2 of membrane of pore size 0.1 µm.). Finally, a reverse osmosis system treats the membrane bioreactor permeate producing water of good quality for any water reuse. Raw wastewater from the full-scale Castell d'Aro WWTP (175000 P.E.), located in Catalonia (NE of Spain), is pumped continuously into the pilot plant to maintain a fixed permeate flux (between 7.5 and 24 L/m^2h).

The pilot plant is fully equipped and automated with online sensors (conductivity, pH, RedOx potential, ammonium, dissolved oxygen, suspended solids, temperature and scum detector), pressure transducers (for transmembrane pressure -TMP- and permeabilty calculation), flow meters and level transmitters, and the use of a PLC and SCADA system that acquires digital and analogical data and controls all the automatic control loops of the plant, mainly the control of aeration, permeate and backwashing fluxes, hydraulic retention time, sludge retention time or mixed liquor suspended solids (biomass) concentration and recycles.

In addition to online data, the routinely monitoring protocol of the pilot plant performance also includes the measurement (of influent and effluent), three times per week, of the rest of the parameters of interest for the supervision of the organic matter and nutrient removal as well as the physical effect of membrane filtration and backwashing: organic matter (TC, TOC, COD and BOD), nitrogen (TKN, ammonium, nitrite and nitrates), phosphate, inorganic carbon, alkalinity, extracellular polymeric substances and suspended solids. Moreover, biological activity and diversity of the biomass is regularly checked.

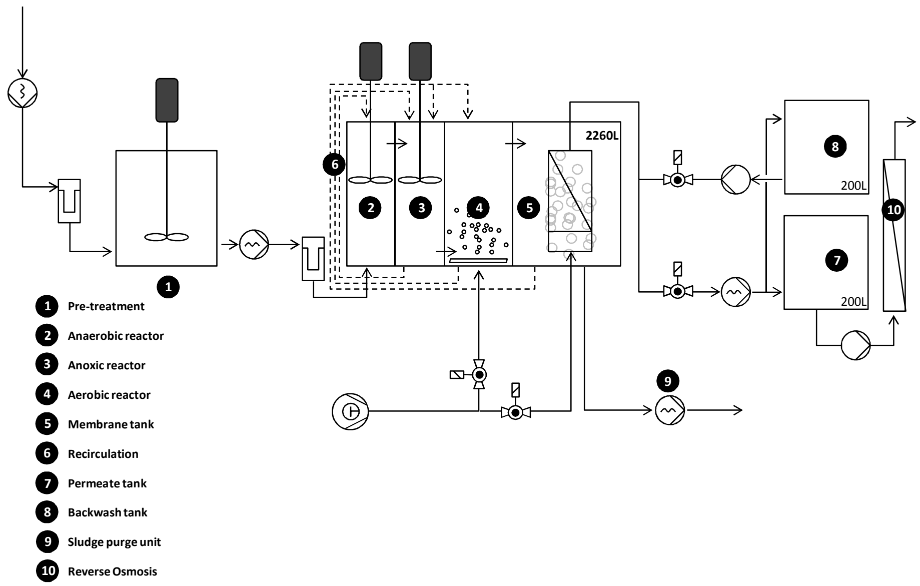

Figure 1. Schematic of the pilot plant under study.

3. IEDSS FOR MEMBRANE BIOREACTORS

The prototype of the intelligent environmental decision support system for membrane bioreactors should guarantee monitoring and real-time robust control, as well as fault detection and remote supervision of the integrated operation of the biological nutrient removal processes and physical filtration and backwashing processes that take place in membrane bioreactors. Figure 2 illustrates the hierarchical control architecture proposed for the intelligent control of membrane bioreactors:

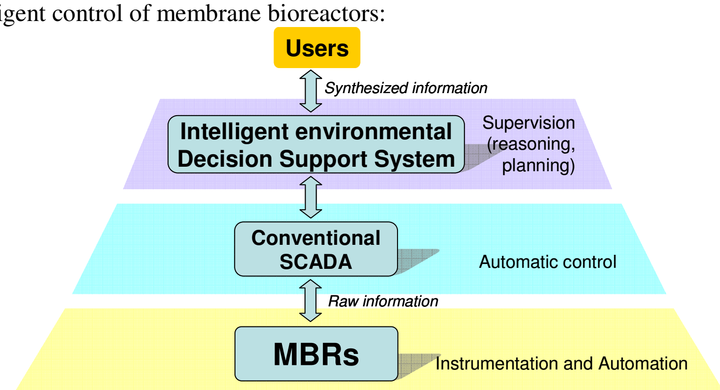

Figure 2. Hierarchical control arquitecture proposed for the integrated control of membrane bioreactors (adapted from [Ayesa *et al.*, 2006]).

The proposed architecture locates the intelligent decision support system hierarchically on top of the conventional supervisory control and data acquisition systems (SCADAs) typically existing in most of the full-scale plants. SCADA systems carry out the acquisition and validation tasks of the data to be used later in the automatic control loops that are implemented (as minimum control of dissolved oxygen in aerobic reactor and, in some cases, control of biomass concentration or sludge age, control of nitrate, control of permeate flux, etc.). The supervisory tasks carried out by the IEDSS allow to establish automatically and in real time the control loop set points needed to optimise the membranes life cycle while, at the same time, ensure reliable and satisfactory nutrient removal. Besides this robust control, the IEDSS allows to detect sensor faults, controller faults and process faults.

The exhaustive list of functionalities that IEDSS for membrane bioreactors should cover includes:

- data acquisition systems throughout communication with SCADAs,
- detection of sensor-related faults,
- advanced (robust) control, establishing the set points of the automatic control loops implemented in the SCADA,
- detection of control loop faults,
- detection of biological, filtration and backwashing process faults,
- automatic learning system,
- to perform daily reports about the plant performance and,
- integration and remote (via Internet) user communication.

4. ARCHITECTURE OF THE IEDSS

The proposed architecture of the IEDSS for membrane bioreactors is based on three levels:

- The first level, called data acquisition, includes the communication and detection of sensor fault modules. The data communication module carries out the tasks involved in the remote data reading and writing throughout communication with SCADA via OPC server and client, and its recording. Different time scales and heterogeneous (both quantitative and qualitative) data should be acquired.

- The second level, called knowledge management, implements the reasoning tasks which, from the available information, allow inferring the process state and afterwards proposing, implementing and simulating a control strategy. The tasks from this level can be carried out thanks to the integrated use of a plant-wide mathematical model (biological process + filtration and backwashing), advanced control algorithms, multivariate statistical techniques and tools from artificial intelligence (rule-based expert systems, model-based reasoning systems and case-based reasoning systems) that allow to optimise the filtration/backwashing and complete nutrient removal processes, whilst supervising controller and process faults (Figure 3).

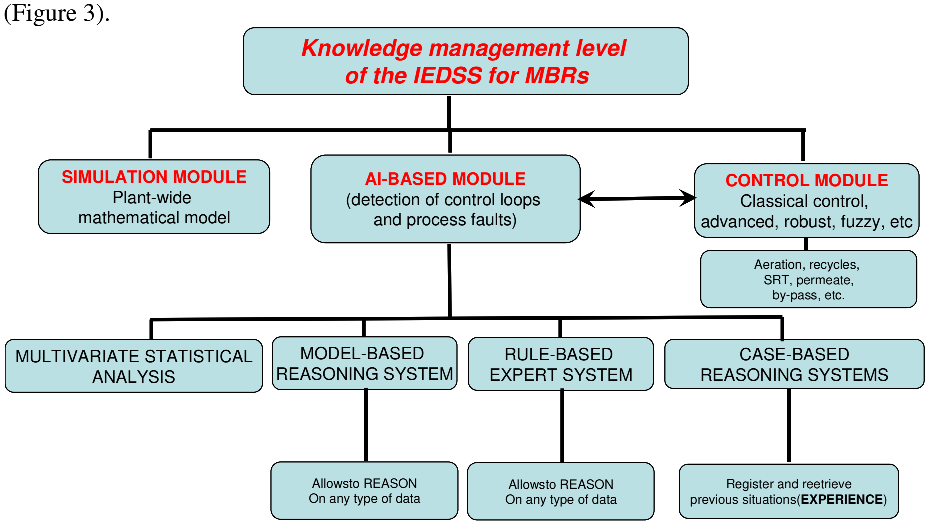

Figure 3. Knowledge management level of the IEDSS for membrane bioreactors.

The rule-based and model-based systems should include 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 -EPS-, washing frequency and type, particle size distribution, etc.). At the same time, the IEDSS is meant to be equipped with an automatic learning module of the membranes life cycle that records and analyses accumulated experiences and allows acquired knowledge to be reused in the future whenever similar situations arise.

- The third level, the support system level, performs the supervision and integration tasks, processing the conclusions from the previous level and proposing the control strategy (set points modification etc.). This level also allows evaluating the control alternatives by means of simulation. The interaction with the end-user is essential in this level, through a remote application (via Internet, www.colmatar.es) with user-friendly and interactive interfaces (Figure 4).

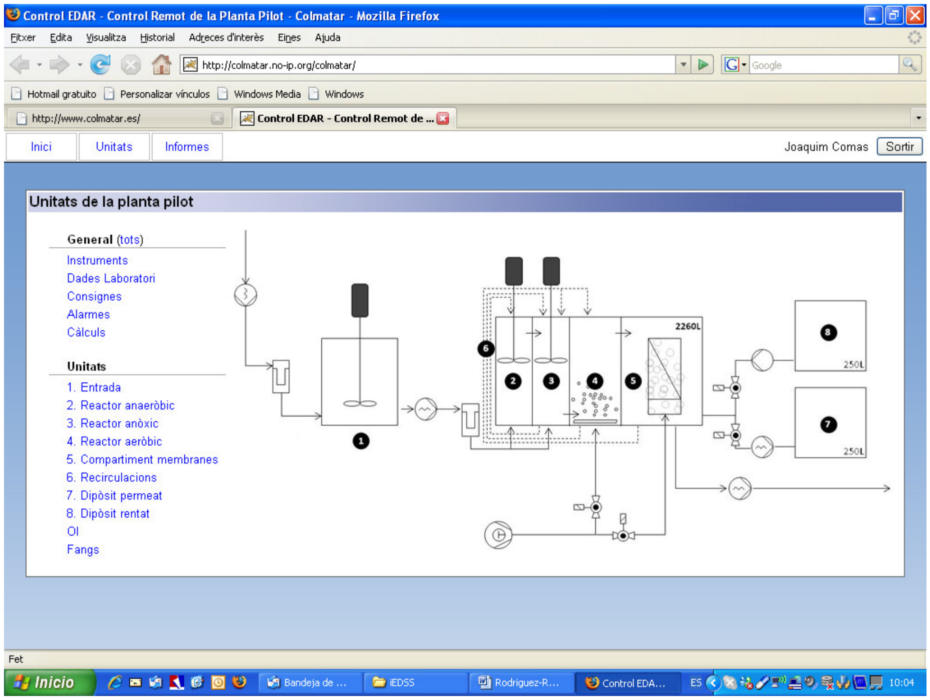

Figure 4. Homepage of the web-based IEDSS for membrane bioreactors.

5. CONTROL MODULE OF THE IEDSS

The control module of the IEDSS governs the automatic or semi-automatic control loops of the most important parameters for the biological and physical processes of membrane bioreactors: dissolved oxygen control, being the aeration flow rate in the aerobic reactor as control action, closed-loop control of permeate and backwashing fluxes, control of feed flow rate (and thus hydraulic retention time), closed-loop control of sludge retention time (or mixed liquor suspended solids or biomass concentration), based on wasting sludge flow rates, and closed-loop control of sludge and nitrate recycles.

The control module of the IEDSS includes the necessary knowledge to fix the set points for all the automatic or semi-automatic conventional controllers of membrane bioreactors (e.g. PI or PID, usually implemented in the SCADA systems) and the new algorithms developed for more advanced controllers (e.g. FLC). The adjustment of control set points (DO, permeate flux, sludge retention time, etc.) can be related to the detection of faults by means of the AI-based module. This way the control module ensures an optimal and robust integrated operation of the membrane bioreactors.

6. AI-BASED MODULE OF THE IEDSS

The use of AI tools and models provides direct access to knowledge and expertise and makes the IEDSS capable of supporting learning and decision making processes. Their integration with numerical and/or statistical models in a single system provides higher reliability [Poch *et al.*, 2004]. This module becomes thus the reasoning core of the IEDSS and it comprises multivariate data analysis, rule-based reasoning, model-based reasoning and case-based reasoning. The aim of this reasoning module is to establish the set of set points for all the control loops or other manual or semi-automatic control actions (e.g. chemical cleaning of the membranes) that continuously ensure lower operational and energy costs while at the same time maintains or improves effluent quality.

6.1 Multivariate data analysis

Multivariate analysis, based on both statistical and AI-related methods, explore historical databases comprised of several types of variables, including physical, chemical and biological data. The aim is to find clear interrelationships among variables in a low-dimensional space and ultimately to study the possibility to ascertain a model of sub-process faults (e.g. problems in the DO control loop due to sensor fault) or process faults (e.g. biofouling indicated by a significant decrease of membrane permeability over time).

6.2 Rule-based expert system

A Rule-Based Expert System (RBES) is a computer program that emulates human expert reasoning processes when making decisions to confront problems, in this case the integrated operation of nutrient removal and membrane filtration. The key part of a RBES is its knowledge base. In this case the knowledge base, mainly built upon specialised literature and multivariate data analysis, will include symptoms and reasoning process to diagnose and propose control strategies for:

- detection of control loop faults,
- detection of typical process faults of the biological nutrient removal (loss of nitrification capacity, bulking, organic shock, etc.).

The detection of these faults may obviously imply set point modifications of the automatic control systems.

- estimation of costs and risks.

6.3 Model-based reasoning system

Due to the ease of its maintenance and reusability, model-based reasoning technique has been identified as more adequate for the development and implementation of the knowledge base for the optimal operation of the physical membrane filtration [Peischl and Wotawa, 2003]. It implies developing an appropriate model for both the filtration and backwashing processes which are abstract enough to be computationally tractable but detailed enough to provide significant diagnosis results for the membrane biofouling rate. Ultimately this part of the knowledge base, based on the factors influencing biofouling (mainly biomass characteristics, wastewater characteristics e.g. EPS, permeate flow and aeration intensity) must maximize the net permeate flux whereas the biofouling and energy consumption are minimized, and thus membrane life-time maximized.

6.4 Case-based reasoning system

The Case-Based learning and Reasoning System (CBRS) of the membranes life-cycle will allow analyzing and registering those significant events relative to the filtration and backwashing processes with the aim to reuse knowledge gained in previous experiences, given that similar situations have to be confronted. This system allows the accumulation of useful experiences for optimisation of the pilot performance. The identification of the most relevant variables in filtration/backwashing processes (such as flux, TMP, permeability, etc.) and the type of experiences that may occur (mainly management of the filtration/backwashing cycle according to the process variables to minimize biofouling and reduce costs) is indispensable for the development of a functional CBRS.

7. SIMULATION MODULE OF THE IEDSS

The simulation module of the IEDSS comprises an integrated model for membrane bioreactors. This integrated model involves the description of the biological nutrient removal processes, based on ASM models, together with the physical processes of filtration and backwashing, including the membrane fouling or clogging phenomena, which are still currently under study [Guglielmi *et al.*, 2007 or Li and Wang, 2007]. The availability of such a model will enable to perform several simulations aimed at acquiring relevant knowledge for the optimisation of the operation and control of membrane bioreactors. Thus the simulation module of the IEDSS for membrane bioreactors is not intended to be used for online control, but for offline scenario analysis.

8. CONCLUSIONS

This paper presents the architecture and development of an IEDSS for the integrated operation of membrane bioreactors. The proposed web-based IEDSS is based on a three-level architecture to integrate on-line, off-line and qualitative information with different knowledge management techniques, control algorithms and mathematical models. The intelligent core of the IEDSS will be based on the acquisition of the relevant knowledge to optimise the membrane life cycle as well as keeping a good level of nutrient removal performance and its representation by means of the rule-based, model-based and case-based AI paradigms.

ACKNOWLEDGEMENTS

This research project has been funded by the Spanish Ministerio de Educación y Ciencia research project (DPI2006-15707-C02-01) and the Spanish Ministerio de Medio Ambiente project (018/SGTB/2007/3.1). Also, the authors want to acknowledge the support of ASEPMA, ATM, Consorci de la Costa Brava, Depuradores d'Osona, INIMA, S.A. and Sisltech, S.L and of the computer scientists (Pere Clara and Jordi Majó).

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