Universitat de Girona

DEVELOPMENT OF A DECISION SUPPORT SYSTEM FOR THE INTEGRATED CONTROL OF MEMBRANE BIOREACTORS

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PhD Thesis

Development of a decision support system for the integrated control of membrane bioreactors

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Certifiquen

Que el llicenciat en Química **Hèctor Monclús Sales** ha realitzat, sota la seva direcció, el treball que amb el títol "**Development of a decision support system for the integrated control of membrane bioreactors**", que es presenta en aquesta memòria la qual constitueix la seva Tesi per optar al Grau de Doctor per la Universitat de Girona.

I perquè en prengueu coneixement i tingui els efectes que corresponguin, presentem davant la Facultat de Ciències de la Universitat de Girona l'esmentada Tesi, signant aquesta certificació a

Girona, 14 Setembre de 2011

Ignasi Rodríguez-Roda Layret

Joaquim Comas Matas

Als meus,

Mama, Pepe, Marc i Natàlia

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RESUM

SUMMARY/RESUMEN

L'increment d'atenció en el tractament de les aigües residuals, així com també la necessitat de la reutilització d'aquest recurs, juntament amb la progressiva reducció de costos, tant d'instal·lació com d'operació, han fet que els bioreactors de membranes, MBR de l'anglès *membrane bioreactor*, es situïn com una tecnologia amb una clara expansió i implementació en el camp del tractament d'aigües residuals urbanes en els darrers anys.

L'elevada qualitat de l'aigua obtinguda i el seu potencial de reutilització fan d'aquesta tecnologia una opció més atractiva front als sistemes convencionals de tractament d'aigües residuals. L'esmentada tecnologia presenta però, certes limitacions que alenteixen la seva expansió, tant en grans nuclis urbans com en petites poblacions descentralitzades.

Històricament la recerca en MBR s'ha centrat principalment en la caracterització dels mecanismes d'embrutiment que pateixen les membranes durant el procés de filtració, així com també en la minimització dels elevats consums energètics.

El treball presentat en aquesta tesi doctoral inclou diversos estudis parcials amb l'objectiu final de ***desenvolupar un sistema d'ajuda a la decisió pel control integrat dels bioreactors de membrana***. Els sistemes d'ajuda a la decisió, SAD o **DSS** de l'anglès, decision support system, tenen com a objectiu facilitar l'operació de processos complexes degut a multitud de variables de procés. Per aquest motiu, la recerca realitzada s'ha centrat en aspectes relacionats amb l'eliminació de nutrients, i en el desenvolupament d'indicadors o sensors pel procés de filtració capaços d'integrar-se amb els processos biològics que hi tenen lloc. També s'ha treballat en el disseny, desenvolupament, implementació i validació d'eines basades en el coneixement que facilitin el control automàtic i la supervisió dels MBR mitjançant un DSS.

La tesi s'ha estructurat en diferents apartats, presentats a continuació, per fer més entenedora la seva comprensió.

El primer apartat està basat en el seguiment i validació dels processos biològics en un MBR. Primerament, es van determinar les condicions d'operació per l'eliminació biològica de nutrients a una planta pilot MBR que tractava aigua residual urbana, treballant tant en estat estacionari com en dinàmic. Les condicions d'operació aplicades al llarg de més de 200 dies d'operació en un MBR amb una configuració University of Cape Town van permetre assolir rendiments d'eliminació de carboni de fins el 96%, pel nitrogen del 89%, i pel fòsfor del 88%, aquest seguiment es va complementar en estudis en discontinuo de les activitats d'eliminació de fòsfor. Per altra banda, la importància de conèixer la concentració de sòlids

del licor mescla en temps real va motivar el desenvolupament d'una metodologia per l'estimació en línia dels sòlids en suspensió als diversos tancs d'un procés biològic.

Un segon apartat de la tesi s'ha destinat al desenvolupament d'eines pel seguiment de l'embrutiment de les membranes. La necessitat de seguir en línia aquest embrutiment va motivar el desenvolupament d'una nova metodologia capaç de monitoritzar-lo de forma més ràpida i fiable. Aquesta metodologia, basada en el seguiment dels pendents de la pressió trans-membrana de cada cicle, va resultar ser una eina ràpida, sensible i eficaç per detectar, mesurar i indicar l'estat de la membrana pel que fa al procés de filtració. Paral·lelament, el potencial de reutilització de l'aigua tractada amb un MBR, va incentivar l'estudi sobre l'impacte que té l'embrutiment sobre els paràmetres de qualitat microbiològics de l'efluent. El resultat va mostrar que l'embrutiment reversible no presenta cap correlació amb la l'eficiència d'eliminació d'indicadors bacterians, degut a la exclusió per mida de porus, mentre que l'embrutiment irreversible fa augmentar els rendiment d'eliminació d'indicadors virals, principalment degut a la reducció de la mida del porus de la membrana.

Finalment, els diferents estudis realitzats i el coneixement extret d'aquesta recerca han permès el desenvolupament i la implementació de diversos mòduls basats en el coneixement per a l'operació d'un MBR. Un d'aquests mòduls va permetre assolir d'una manera automàtica la concentració de sòlids desitjada en el tanc de membranes d'un MBR de membranes planes en només tres setmanes, minimitzant el fenomen de l'embrutiment.

Per acabar, es presenta la definició de l'estructura jeràrquica del sistema d'ajuda a la decisió, on també s'expliquen els diferents mòduls desenvolupats al llarg dels dos projectes de recerca del ministerio de educación y ciencia (MEC) i del ministerio de ciencia e innovación (MICINN) (DPI2006-15707-C02-01 i CTM2009-14742-C02-01) en que aquesta tesi s'ha desenvolupat.

La recerca presentada en aquesta tesi ha permès extreure i adquirir coneixement de tots els resultats per complementar el DSS i està encaminada a facilitar, optimitzar, controlar i operar de forma integrada els MBR.

RESUMEN
SUMMARY/RESUM

El incremento de la atención en el tratamiento de las aguas residuales, así como también la necesidad de la reutilización de este recurso, juntamente con la progresiva reducción de los costes, tanto de instalación, como de operación, han hecho que los biorreactores de membrana (MBR) si sitúen, en los últimos años, como una tecnología con clara expansión e implementación en el campo del tratamiento de aguas residuales urbanas.

La elevada calidad del agua obtenida y su potencial de reutilización hacen de esta tecnología una opción más atractiva frente a los sistemas convencionales de tratamiento de aguas residuales. Dicha tecnología presenta ciertas limitaciones que ralentizan su expansión, tanto en grandes núcleos urbanos, como en pequeñas poblaciones descentralizadas.

La investigación en MBR se ha centrado, principalmente, en la caracterización de los mecanismos de ensuciamiento que sufren las membranas durante el proceso de filtración, así como también en la minimización de los elevados consumos energéticos.

El trabajo presentado en esta tesis doctoral incluye diversos estudios parciales con el objetivo final de ***desarrollar un sistema de ayuda a la decisión para el control integrado de los biorreactores de membrana***. Los sistemas de ayuda a la decisión, SAD o DSS del inglés decision support system, tienen como objetivo facilitar la operación de procesos complejos debido a la multitud de variables que se procesan. Por este motivo, la investigación se ha centrado en el desarrollo de indicadores o sensores capaces de integrarse con los procesos biológicos que tienen lugar, así como también, en aspectos relacionados con la eliminación de nutrientes. Además, se ha trabajado en el diseño, desarrollo, implementación y validación de herramientas basadas en el conocimiento que faciliten el control automático y la supervisión de los MBRs mediante un DSS.

La tesis se ha estructurado en diferentes apartados para facilitar su comprensión.

El primer apartado se basa en el seguimiento y validación de los procesos biológicos en un MBR. En primer lugar, se determinaron las condiciones de operación para la eliminación biológica de nutrientes (carbono, nitrógeno y fósforo) en una planta piloto MBR que trataba agua residual urbana, trabajando tanto en estado estacionario como en dinámico. Las condiciones de operación aplicadas a lo largo de más de 200 días de operación con una configuración *University of Cape Town* permitieron conseguir rendimientos de eliminación de carbono de hasta el 96%, del 89% para el nitrógeno y del 88% para el fósforo, este seguimiento se complementó con estudios en discontinuo de las actividades de eliminación del fósforo. Por otra parte, la importancia de conocer la concentración de sólidos del licor

mezcla en tiempo real motivó el desarrollo de una metodología para la estimación en línea de los sólidos en suspensión en los diversos compartimientos de un proceso biológico.

El segundo apartado de la tesis se ha destinado al desarrollo de herramientas para el seguimiento del ensuciamiento de las membranas. La necesidad de seguir en línea dicho ensuciamiento motivó el desarrollo de una nueva metodología capaz de monitorizar-lo de forma más rápida y fiable. Dicha metodología, basada en el seguimiento de las pendientes de la presión trans-membrana de cada uno de los ciclos de permeado, resultó ser una herramienta rápida, sensible y eficaz para detectar, medir e indicar el estado de la membrana por lo que al proceso de filtración se refiere. Paralelamente, el potencial de reutilización del agua tratada con un MBR, incentivó el estudio sobre el impacto que tiene el ensuciamiento sobre los parámetros de calidad microbiológica del agua tratada. El resultado mostró que el ensuciamiento reversible no presenta ninguna correlación con la eficiencia de eliminación de indicadores bacterianos, mientras que el ensuciamiento irreversible aumenta los rendimientos de eliminación de indicadores virales, principalmente debido a la reducción del tamaño de poro de la membrana.

Finalmente, los diferentes estudios realizados y el conocimiento extraído de esta investigación han permitido el desarrollo y la implementación de diversos módulos basados en el conocimiento para la operación de un MBR. Uno de estos módulos permitió alcanzar de forma automática la concentración de sólidos deseada en el tanque de membranas en tan solo tres semanas, minimizando el ensuciamiento.

Para terminar, se presenta la definición de la estructura jerárquica del sistema de ayuda a la decisión, donde también se explican los diferentes módulos desarrollados a lo largo de este estudio, el cuál ha sido financiado por el ministerio de educación y ciencia (MEC) y el ministerio ciencia e innovación (MICINN) DPI2006-15707-C02-01 y CTM2009-14742-C02-01, a lo largo de estos últimos 4 años.

La investigación presentada en esta tesis ha permitido la adquisición de conocimiento de todos los resultados para complementar el DSS y está orientada en facilitar, optimizar, controlar y operar de forma integrada los MBR.

SUMMARY
RESUM/RESUMEN

The increasing attention paid to the treatment of wastewater, the need to reuse this resource, and the progressive reduction of both installation and operating costs have positioned membrane bioreactors (MBRs) as a clearly expanding and widely used technology in the area of urban wastewater treatment in recent years.

The high quality of the water obtained and the potential for its reuse make this a more attractive option than conventional wastewater treatment systems. The technology, however, has certain limitations that have slowed down its expansion, both in large urban centres and small decentralised towns and villages.

Research into MBRs has focused primarily on the description of the fouling mechanisms the membranes are subjected to during the filtration process, as well as on reducing the high energy consumption.

The work presented in this PhD thesis includes various partial studies aimed at ***developing a decision support system for membrane bioreactor integrated control***. The decision support systems (DSS) have as a main goal to facilitate the operation of complex processes due to the multiple variables that are processed. For this reason, the research used has focused on aspects related to nutrient removal, and on the development of indicators or sensors capable of facilitating, automating and controlling the filtration process in an integrated way with the biological processes that taking place. Work has also been done on the design, development, implementation and validation of tools based on the knowledge made available by the automatic control and the supervision of the MBRs.

The thesis is organised into different sections to make it easier to follow and understand.

The first section is based on the monitoring and assessment of the biological processes in an MBR. First, the operating conditions were determined for the biological removal of nutrients in an MBR pilot plant that treats urban wastewater, functioning in both steady and unsteady states. The operating conditions applied during the more than 200 days of operation in an MBR with a University of Cape Town configuration led to a carbon removal of up to 96%, nitrogen removal of 89%, and phosphorous removal of 88%. The monitoring of phosphorous removal allowed a validation of the operating conditions of the MBR as adequate for the development of the biomass responsible for the bioaccumulation of phosphorous. In addition, the importance of knowing the solids concentration of the mixed liquor in real time motivated the development of a method for the online estimation of the suspended solids in various tanks of a biological process.

As second section of the thesis is focused on the development of tools to monitor membrane fouling. The need for online monitoring led to the development of a new, quicker and more reliable method. This method, based on the monitoring of the trans-membrane pressure slope of each cycle, proved to be a fast, sensitive and efficient tool to detect, measure and indicate the state of the membrane in terms of the filtration process. Likewise, the potential to reuse water treated by an MBR provided incentive for the study of the impact of fouling on the microbiological quality parameters of the effluent. The result demonstrated that reversible fouling has no correlation with the efficiency of the removal of bacterial indicators, due to pore size exclusion, while the irreversible fouling increases the viral indicators removal efficiency, primarily due to the reduction of the of the pore size of the membrane.

Finally, the various studies undertaken and the knowledge extracted from this research have allowed the development and the implementation of various knowledge-based modules for the operation of an MBR. One of these modules permitted automatic achievement of the desired solids concentration in the membrane tank of an MBR with flat membranes in only three weeks, minimizing the fouling phenomenon.

To end, the definition of the hierarchical structure of the decision-support system is presented. There the different modules developed during these two research projects of the Ministry of Education and Science (MEC) and the Ministry of Science and Innovation (MICINN), in which this thesis has been developed, are also explained (DPI2006-15707-C02-01 and CTM2009-14742-C02-01).

The research presented in this PhD thesis has allowed to obtain knowledge from all of the results to complement the DSS, and it is oriented to facilitate, optimise, control and manage, in an integrated way, the MBRs.

Table of CONTENTS

List of Publications

The following list contains the publications presented as chapters of this PhD thesis, together with the contributions of the PhD candidate in each paper:

Monclús, H., Sipma, J., Ferrero, G., Comas, J. and Rodriguez-Roda, I. (2010). "Optimization of biological nutrient removal in a pilot plant UCT-MBR treating municipal wastewater during start-up." Desalination **250**(2), 592-597.

Author's Contribution: All the experimental study and data analysis. Writing the paper, with contributions from the other authors.

Monclús, H., Sipma, J., Ferrero, G., Rodriguez-Roda, I. and Comas, J. (2010). "Biological nutrient removal in an MBR treating municipal wastewater with special focus on biological phosphorus removal." Bioresource Technology 101(11), 3984-3991.

Author's Contribution: All the experimental study and data analysis. Writing the paper, with share contributions from J. Sipma.

Beltrán, S., Irizar, I., **Monclús, H.**, Rodriguez-Roda, I. and Ayesa, E. (2009). "On-line estimation of suspended solids in biological reactors of WWTPs using a Kalman observer." Water Science and Technology **60**(3), 567-574.

Author's Contribution: The experimental study to validate the developed Kalman filter. The design and development the Kalman filter were performed by: S. Beltran, I. Irizar and E. Ayesa. Writing of the paper, with contributions from the other authors.

Monclús, H., Ferrero, G., Buttiglieri, G., Comas, J. and Rodriguez-Roda, I. (2011). "Online monitoring of membrane fouling in submerged MBR." Desalination **277**(1-3), 414-419.

Author's Contribution: Planning and following-up of the experimental study and analysis of the results. Writing the paper, with contributions from the other authors.

Marti, E., **Monclús, H.**, Jofre, J., Rodriguez-Roda, I., Comas, J. and Balcazar, J. L. (2011). "Removal of microbial indicators from municipal wastewater by a membrane bioreactor (MBR)." Bioresource Technology **102**(8), 5004-5009.

Author's Contribution: Monitoring the plant and data collection. All the lab analyses were performed by E. Marti. Writing the paper, with contributions from the other authors.

Monclús, H., Buttiglieri, G., Ferrero, G., Rodriguez-Roda, I. and Comas, J. (2011). "Knowledge-based control module for start-up of flat sheet MBRs" Submitted in Journal of Bioresource Technology/**BITE-D-11-02597.**

Author's Contribution: All the decision tree development and implementation and the analysis of the results. Writing the paper, with contributions from the other authors.

Comas, J., Meabe, E., Sancho, L., Ferrero, G., Sipma, J., **Monclús, H.** and Rodriguez-Roda, I. (2010). "Knowledge-based system for automatic MBR control." Water Science and Technology **62**(12), 2829-2836.

Author's Contribution: Developing all the modules (assisted by G. Ferrero). Writing the paper, with contributions from the other authors.

Additional relevant publications but not included as chapters:

Muñoz, J., **Monclús, H.**, Forrero, G., Plensa, M., Rovira, S., Comas, J. and Rodríguez-Roda, I. (2008). "Integrated membrane bioreactor control: For the elimination of nutrients in wastewater." Ingeniería Química **460**, 124-129.

Canals, J., Ferrero, G., Rovira, S., **Monclús, H.**, Comas, J. and Rodríguez-Roda, I. (2010). "Sistema de control avanzado para la optimización energética de biorreactores de membranas." Ingeniería Química **478**, 66-72.

Sipma, J., Osuna, B., Collado, N., **Monclús, H.**, Ferrero, G., Comas, J. and Rodriguez-Roda, I. (2010). "Comparison of removal of pharmaceuticals in MBR and activated sludge systems." Desalination **250**(2), 653-659.

Monclús, H., Zacharias, S., Santos, A., Pidou, M. and Judd, S. (2010). "Criticality of flux and aeration for a hollow fiber membrane bioreactor." Separation Science and Technology **45**(7), 956-961.

Ferrero, G., **Monclús, H.**, Buttiglieri, G., Comas, J. and Rodriguez-Roda, I. (2011). "Automatic control system for energy optimization in membrane bioreactors." Desalination **268**(1-3), 276-280.

Ferrero, G., **Monclús, H.**, Sancho, L., Garrido, J. M., Comas, J. and Rodríguez-Roda, I. (2011). "A knowledge-based control system for air-scour optimisation in membrane bioreactors." Water Science and Technology **63**(9), 2025-2031.

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List of ACRONYMS

BOD	*biochemical oxygen demand*
C	*carbon*
COD	*chemical oxygen demand*
DO	*dissolved oxygen*
EPS	*extra polymeric substance*
F/M	*food to microorganisms ratio*
FS	*flat sheet*
HF	*hollow fiber*
J	*flux*
Jc	*critical flux*
K	*permeability*
KB	*knowledge-based*
HRT	*hydraulic retention time*
MBR	*membrane bioreactor*
MF	*microfiltration*
MLSS	*mixed liquor suspended solids*
MLVSS	*mixed liquor volatile suspended solids*
MT	*multi tubular membrane*
N	*nitrogen*
NF	*nanofiltration*
ORP	*oxidoreduction potential*
P	*phosphorous*
PAO	*phosphate accumulating organism*
PLC	*programmable logic controller*
PP	*polypropylene*
PS	*polysulphone*
PVDF	*polyvinylidene difluoride*
SAD	*specific aeration demand*
SCADA	*supervisory control and data acquisition*
SMP	*soluble microbial products*
SRT	*solids retention time*
TMP	*transmembrane pressure*
TN	*total nitrogen*
TSS	*total suspended solids*
UCT	*University of Cape Town*
UF	*ultrafiltration*
VSS	*volatile suspended solids*
WWTP	*wastewater treatment plant*

Chapter 1
Introduction

This chapter presents a general introduction of the MBR technology and gives the justification and the motivation for this thesis.

1.1. Membrane Bioreactor (MBR) Technology

Membrane bioreactor (MBR) technology in municipal wastewater treatment is currently challenging traditional methods, due to the recent technical innovations in and the strong cost reductions of the membranes used (Fane and Fane 2005). An undesired overloading of existing conventional activated sludge (CAS) treatment plants by increased population densities in areas with limited land available could be overcome relatively easy by upgrading existing CAS plants to MBR configurations, significantly increasing the total plant capacity (Zhang *et al.,* 2003; Judd 2011).

The use of membrane bioreactors is a very interesting option for wastewater treatment and reclamation as they efficiently combine the oxidation of organic matter with suspended solids and nutrient removal (Lesjean *et al.,* 2003; Zhang *et al.,* 2009) and microbial decontamination (Lovins Iii *et al.,* 2002). In particular, it can be the preferred choice, compared to other combinations of both conventional or intensive and natural or extensive technologies, when, in addition to water reuse application and microbial quality disinfection (Wintgens *et al.,* 2005; Brissaud 2010).

1.1.1. Fundamentals of MBR technology

MBR technology is characterised by the use of an ultrafiltration (UF) or a microfiltration (MF) unit, depending on the pore size, instead of a conventional settler. In Figure 1.1 a schematic overview compares CAS systems and MBR technology.

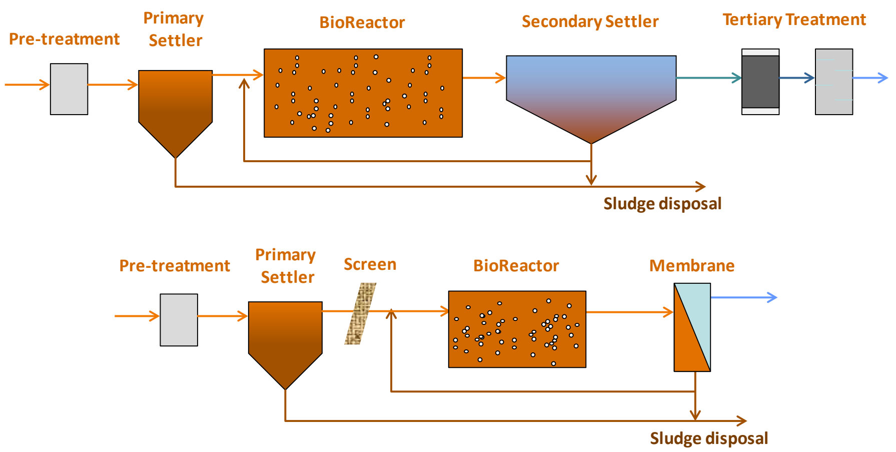

Figure 1.1 Schematic diagram comparing conventional activated sludge systems (CAS) and membrane bioreactors systems (MBR).

A membrane applied to wastewater or water treatment is simply a material that allows some physical or chemical components to pass more readily through it than others. It is thus perm-selective, since it is more permeable to those constituents passing through it than to those rejected by it. The degree of selectivity depends on the membrane pore size (Figure 1.2).

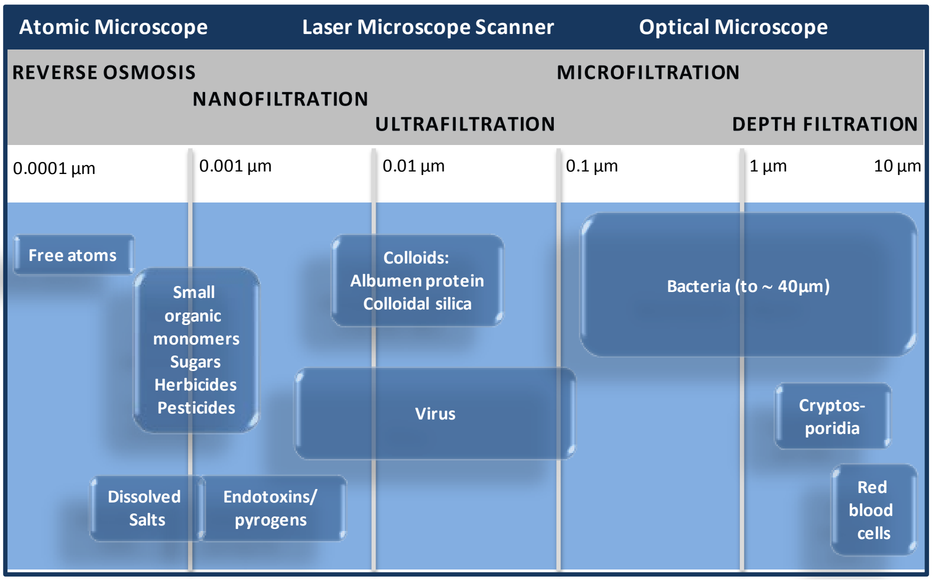

Figure 1.2 Selectivity of the membrane pore size. Adapted from (Judd 2011).

MBR technology offers several advantages over CAS plants, e.g. operation at **high biomass concentrations** (Witzig *et al.,* 2002), **reduced** excess **sludge production** (Wagner and Rosenwinkel 2000), extremely **low suspended solid (SS) concentrations** in treated effluent (Gander *et al.,* 2000), drastically enhanced **elimination of pathogens** and **viruses** (Côté *et al.,* 2004; Melin *et al.,* 2006), and a **superior effluent quality** (Jefferson *et al.,* 2001; Schröder 2002; Côté *et al.,* 2004). Additionally, the high biomass concentration and long sludge retention times (SRT) in MBR plants positively affect the overall activity of slow growing microorganisms acting in nitrification (Côté *et al.,* 2004) or the **degradation** of **specific refractory** pollutants (Schröder 2002; Clara *et al.,* 2004; Sipma *et al.,* 2010). Schröder (2002) suggested that membrane systems provide a competitive advantage for organisms capable of degrading recalcitrant compounds by eliminating bacterial washout. However, these systems are obviously governed by the required sludge wastage to maintain a more or less constant biomass concentration in the MBR, thus limiting the SRT. Furthermore, the high biomass concentrations in an MBR not merely leads to decreased sludge production, but also a higher stability and persistence to shock loads (Lee *et al.,* 2003; Melin *et al.,* 2006).

1.1.2. Configurations of MBR technology

It is primarily in the area of water reuse, or applications demanding high quality of treated effluent, where MBRs have been successful. MBRs combine conventional biotreatment with membrane separation either outside (Figure 1.3A) or inside the biotank (Figure 1.3B).

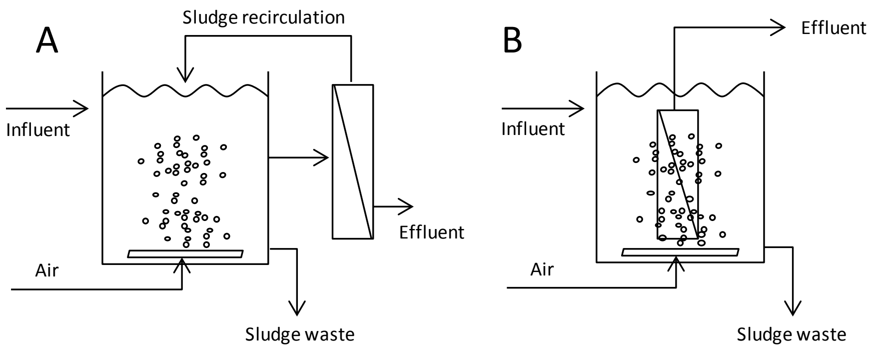

Figure 1.3 Membrane Bioreactors Configurations. **A** external, **B** immersed (iMBR).

The membranes are normally either planar (hence flat sheet, ***FS***) or cylindrical (hence hollow fibre, ***HF***) if they are internally placed, or multi-tube (***MT***) if external (Figure 1.4).

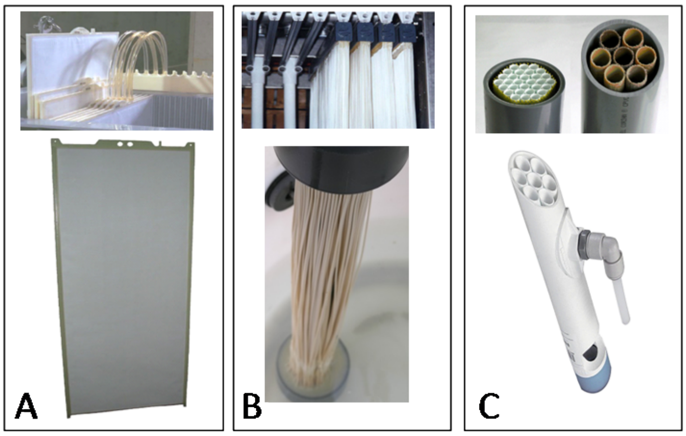

Figure 1.4 Membrane configurations. **A)** Flat sheet-FS, **B)** Hollow fibre-HF, **C)** Multi tubular-MT.

1.1.3. Operational parameters

When working with an MBR some very important and useful parameters have to be monitored. These parameters are listed below:

- **Permeate flux (*J*)** is the flow through a specific membrane surface. Usually expressed as *LMH*.

$$Flux = \frac{flow\ (L/h)}{surface\ (m^2)} = [L{\cdot}m^{-2}{\cdot}h^{-1}]\ \text{highly used as}\ [LMH]$$

- **Transmembrane pressure (*TMP*)** is the pressure that it is necessary to apply to obtain a specific flux. It is usually expressed in bars.

- **Membrane Permeability (*K*)** is the relation between the flux (*J)* and the *TMP.*

$$Permeability = \frac{flux}{TMP} = [LMH{\cdot}bar^{-1}]$$

- **Specific aeration demand (SADm)** the airflow with respect to membrane area.

$$SADm = \frac{air\,flow\ (m^3/h)}{surface\ (m^2)} = [m{\cdot}h^{-1}]$$

1.1.4. MBR technology limitations

The MBR technology has several positive aspects that make it a good technology for urban wastewater treatment systems, but there are some limitations to market expansion.

In most membrane filtration processes the permeate flux declines during filtration due to **membrane fouling** (Le-Clech *et al.,* 2006; Melin *et al.,* 2006; Wang *et al.,* 2007; Meng *et al.,* 2009; Judd 2011). Fouling is inherent in membrane processes per se, arising from either the deposition of material on the membrane surface that forms a relatively impermeable layer or occlusion of the membrane pores (Judd 2008). These phenomena tend to increase the **resistance** of the membrane to flow (i.e. reduce its permeability) and thus reduce process efficiency, manifested as an **increased energy** demand, increased **frequency of chemical cleaning** requirements and a reduced overall membrane **lifetime**. Therefore, the ability to reduce or control membrane fouling will lead to the implementation of high-end MBR treatment systems.

Fouling is significantly influenced by 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 (Le-Clech *et al.,* 2006; Meng *et al.,* 2009). But, operating conditions (i.e., SRT, hydraulic retention time (HRT) and F/M) and feed water act indirectly on membrane fouling by modifying sludge characteristics (Meng *et al.,* 2009). Le-Clech *et al.* (2006) and Meng *et al.* (2009) concluded that fouling phenomena are extremely complex in MBRs due to the large number of contributing factors and causes, which can be summarised into four groups: membrane materials, biomass characteristics, feed water characteristics and operating conditions. The complex interactions between these aspects complicate the understanding of membrane fouling. Hence, the control and detection of membrane fouling are key issues in MBR operation.

In addition, fouling, clogging (accumulation of solids within the membrane channels) and cleaning all pertain to the maintenance of membrane permeability, and this is primarily sustained through membrane aeration. Aeration is a major parameter for the hydraulic and biological process components, as well as for the scouring of the membrane surface, increasing, significantly, the energy demand and **membrane replacement** (Santos 2010; Verrecht *et al.,* 2010).

1.1.5. Operational costs and market development

Even though economical aspects made MBR technology too expensive to be implemented, the **cost** of the MBR is **decreasing** year after year, converting the MBR technology into a big rival of CAS (Figure 1.5).

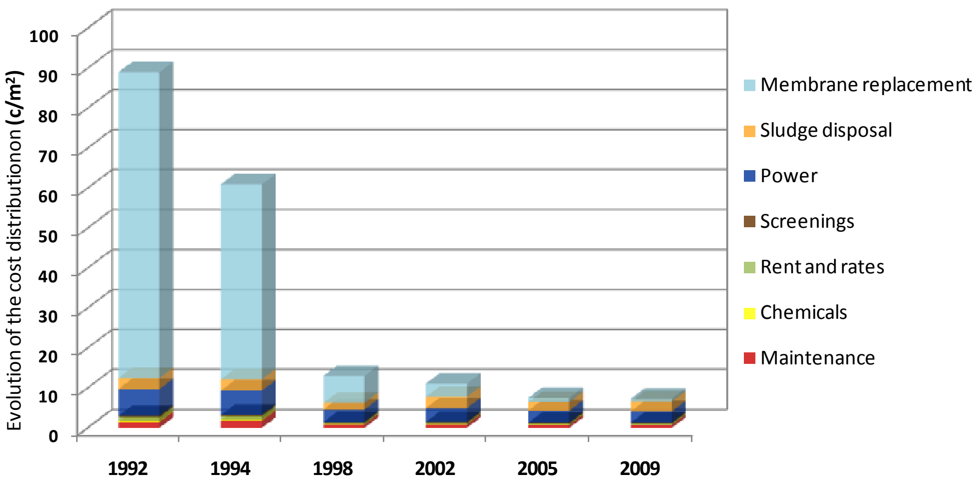

Figure 1.5 Evolution of the total cost and its distribution, adapted from (Verrecht 2009).

The decreasing costs, especially of membrane modules, entailed led to **high market expansion** and membrane implementation (Figure 1.6). The percentage distribution of the costs, at the beginning of the MBR market, was limited due to the high cost of the membrane module (~86% of total costs).

Now, the high percentage of the costs is related with the **energy demand** (~40%), and the membrane cost has declined to 15% (Figure 1.5). After energy, the other factor that has led to higher costs is the **pre-treatment**. After the first MBR, it was realised that very good pre-treatments were necessary. For this reason a small coarse screen and more sophisticated equipment were installed, thus increasing the percentage cost (from 0.4% up to 3.2%) (Verrecht 2009). Consequently the membrane life increased due to the reduction of clogging as a result of the limited pre-treatment.

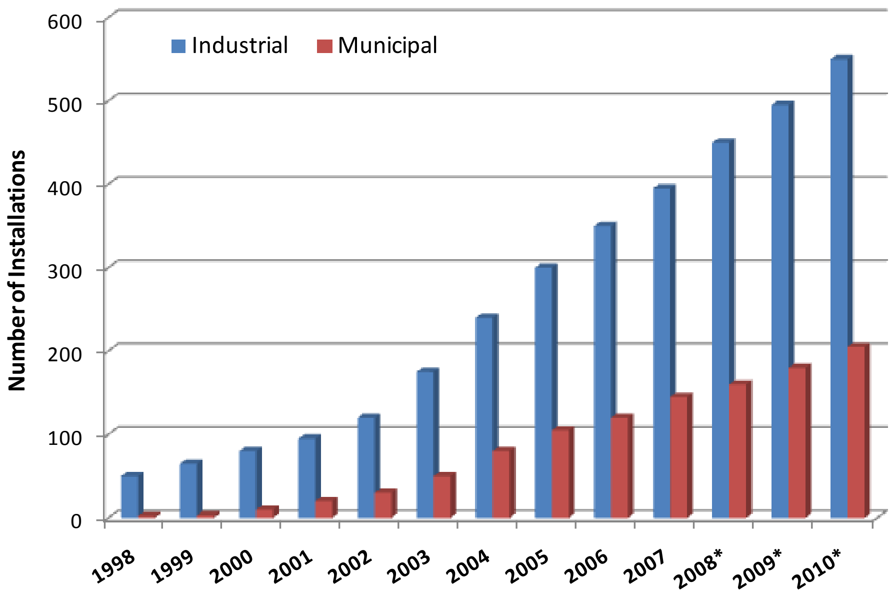

Figure 1.6. Market evolution, adapted from (Verrecht 2009). *Estimation.

These are the factors that led to the market expansion, as much with urban as with industrial treatment. Figure 1.6 shows the market evolution. Fifteen years ago the market was based on industrial treatment, but after the improvements and the reduced the costs of the installation, the urban installations increased. From 2001 to 2005 they increased by around 400%, and until today it is estimated to be as high as to 900%.

Furthermore, in view of wastewater as a renewable source to alleviate water scarcity, especially in dry climates, MBR effluent presents a superior source for water reclamation (Zhang *et al.,* 2003; Côté *et al.,* 2004). Besides, an important growth sector for MBR applications is foreseen in its use in decentralised wastewater treatment and reuse in the near future (Judd 2005; Melin *et al.,* 2006).

1.1.6. Automatic control systems for membrane bioreactors

Membrane **fouling control** and **saving energy** are the key issues in MBR operation. Until now a few studies and inventions aimed at minimising costs end enhancing MBR efficiency have been published or patented. Due to the complex mechanisms of fouling (**section 1.1.4**), it is still not possible to clearly describe how it occurs (and still extremely difficult to build a deterministic model), but it is known that fouling is responsible for permeability loss (Ferrero *et al.*, 2011a).

MBR systems usually involve fixed filtration sequences and aeration, generally proposed by membrane suppliers or selected according to the operator's experience. Furthermore, fouling in an MBR, in practice, can be minimised by sub-critical flux operation, by limiting the flow through the membrane and aerating the membranes to promote turbulence, which acts to scour and/or agitate them (Meng *et al.*, 2009). This frequently results in sub-optimal performance.

Some **control systems** have been engineered for membrane bioreactors, but none has been fully validated in full scale facilities. The great majority of the control systems analysed by Ferrero (2011) can be implemented using the instrumentation and signals already existing in a conventional MBR, with no additional cost, and only a few of the control systems previously described use external devices to measure membrane performance.

The advanced control systems are based on control of one of the following:

- Air-scouring
- Filtration cycles
- Permeate flux
- Chemical cleanings
- Biological nutrient removal (BNR)

Air-scour control systems use, as a changeable variable, the aeration flow or cycles, and filtration cycle control systems use, as a changeable variable, the backwash and filtration length. Both use filtration resistance, permeability and TMP as control variables.

On the other hand, chemical cleaning controls use resistance as a monitored variable to detect the need to apply chemical cleanings.

Finally, BNR control systems use SRT, mixed liquor suspended solids (MLSS) and dissolved oxygen (DO) to modify the sludge waste, membrane recycles and biological aeration.

Generally, there is no mention of **integrated control systems** in the literature, which can be counted on to optimise the filtration process and at the same time control biological nutrient removal. Hence, more research is still necessary to find out or develop different control parameters such as fouling indicators to increase knowledge about and make MBR detection, and consequently MBR control, easier, thereby reducing operational costs and bringing MBR systems to a very competitive level on both small and large scale.

In addition, on-line information in membrane bioreactor plants is, in most cases, insufficient to efficiently monitor, operate and control the process. In order to overcome these limitations "software sensors" can be developed. Software sensors based on state observers have been developed to follow the time evolution of variables and/or parameters of the plant that are not accesible from on-line measurements (Dochain and Vanrolleghem 2001). Through monitoring and automatic control they provide additional information ("from data to information") to optimise the operating process and detect disturbances (Irizar *et al.,* 2008).

1.2. Decision Support Systems (DSS)

Decision support systems (DSS) are multi-level knowledge-based computer systems which not only improve the consistency and the quality of decisions but also reduce decision-making time (Poch *et al.,* 2004). DSS can be applied in multiple scenarios and different research ways. Specifically, DSS have been widely used in the water management domain. Srinivasulu and Jain (2006) used DSS techniques to model the rainfall-runoff. Dixon (2005) applied fuzzy systems for predicting groundwater vulnerability. DSSs were also applied in natural systems (Turon *et al*., 2007) or to model the rainfall (Chang *et al.,* 2005). Giupponi *et al*., (2004) integrated hydrological models and algorithms for DSS. Specialised literature also offers other references were DSS techniques have been used in the wastewater management field (e.g. Comas *et al*., (2004), were decision trees (DT), as causal chains of interactions from symptoms to problems, causes and solutions to diagnosis, were used to model deflocculating problems, or Martínez *et al.*, (2006a), where a DSS was applied to solve activated sludge solids separation problems using case-based reasoning (CBR).

Some of the limitations with conventional automatic control systems can be overcome through the use of **artificial intelligence** (AI) techniques. Knowledge-based DSSs have given successful results due to their ability to represent heuristic reasoning and to work with large amounts of symbolic, uncertain and inexact data, as well as qualitative information that human operators comprehend best, such as fouling problems (Cortés *et al.,* 2000). They also permit implementation of human-like control strategies. Conventional or classical control methods cannot deal with these tasks. One of their main goals is therefore to assist decision-makers in choosing between alternative beliefs or actions by applying knowledge about the decision domain to arrive at recommendations for the various options (Martínez 2005; Martinez *et al.,* 2006a; Martínez *et al.,* 2006b).

1.3. Thesis motivation and hypothesis

The following lists of benefits and drawbacks can serve as a summary of the different aspects related to MBR technology presented in the previous sections:

✓

High quality MBR effluent has been successful as a renewable source to counter water scarcity.

The MBR technology is gaining ground against conventional activated sludge systems, in terms of nutrient removal and higher disinfection.

MBR technology is an emerging market.

Knowledge-based systems (KBS) and decision support systems (DSS) have been successfully applied for WWTP systems as complex systems.

✗

MBR presents some limitations, such as high energy consumption (chemicals, operation) and membrane fouling.

There is limited knowledge about filtration process and nutrient removal requirements.

A large amount of data and information is produced in MBRs but not converted into a useful knowledge.

Although automation is inherent in MBRs, there is a lack of control integration and optimisation.

Gaining ground on the MBR implementation and overcoming the limitations listed above, we can make the following initial hypothesis:

Integrated control of filtration and biological nutrient removal processes will improve the performance and reduce the costs of MBR technology.

To achieve it, it is necessary to work on the following issues:

- Improve the theoretical and practical knowledge related to BNR using an MBR
- Improve the basic and practical knowledge related to fouling
- Evaluate the usefulness of MBR for water reuse requirements
- Improve practical knowledge related to the integrated operation and control of MBRs during unsteady situations such as start-up periods
- Develop a DSS for integrated control and remote supervision of MBRs for wastewater treatment and reuse

Chapter 2

Objectives

In this chapter, the main objective and sub-objectives of the thesis are described.

The main objective of this thesis is to **develop a DSS for MBR integrated control and supervision**.

To achieve this, it was previously necessary to define the following ***sub-objectives***:

- To evaluate the operational conditions using an MBR with the UCT configuration focusing on phosphorous removal and working under unsteady and steady states.
- To develop observers or indicators for filtration and biological performance.
- To evaluate the impact of the fouling on the water quality for reuse requirements.
- To organise and integrate all knowledge acquired into a computational tool for remote MBR integrated control
- To develop knowledge-based modules to supervise the MBR DSS.
- To design an architecture for the DSS.

For this reason the thesis has been divided in three different blocks:

- ***BLOCK I: Biological performance using MBRs***

The main goal of this first block was to evaluate and validate the operational conditions for BNR purposes, using model techniques, in the UCT-MBR pilot plant (**Chapter 3 and Chapter 4**).

A generic Kalman observer was designed and validated in a pilot plant for the on-line estimation of solids concentration (**Chapter 5**).

- ***BLOCK II: Fouling indicators***

The main goal of this second block was to study filtration in terms of fouling indicators (**Chapter 6**) and then to relate these outcomes with the evaluation on the retention of viral and bacterial indicators for water reuse purposes (**Chapter 7**).

- ***BLOCK III: DSS for MBR integrated control and supervision***

The last block of this thesis integrates some of the outcomes of the previous chapters into the computational support tool.

A knowledge-based module is developed and validated to minimise the fouling in a period of high fouling occurrence (start-up periods) (**Chapter 8**). Finally, the architecture of the DSS is presented in **Chapter 9**.

Figure 2.1 presents the relationships between the different chapters of the thesis.

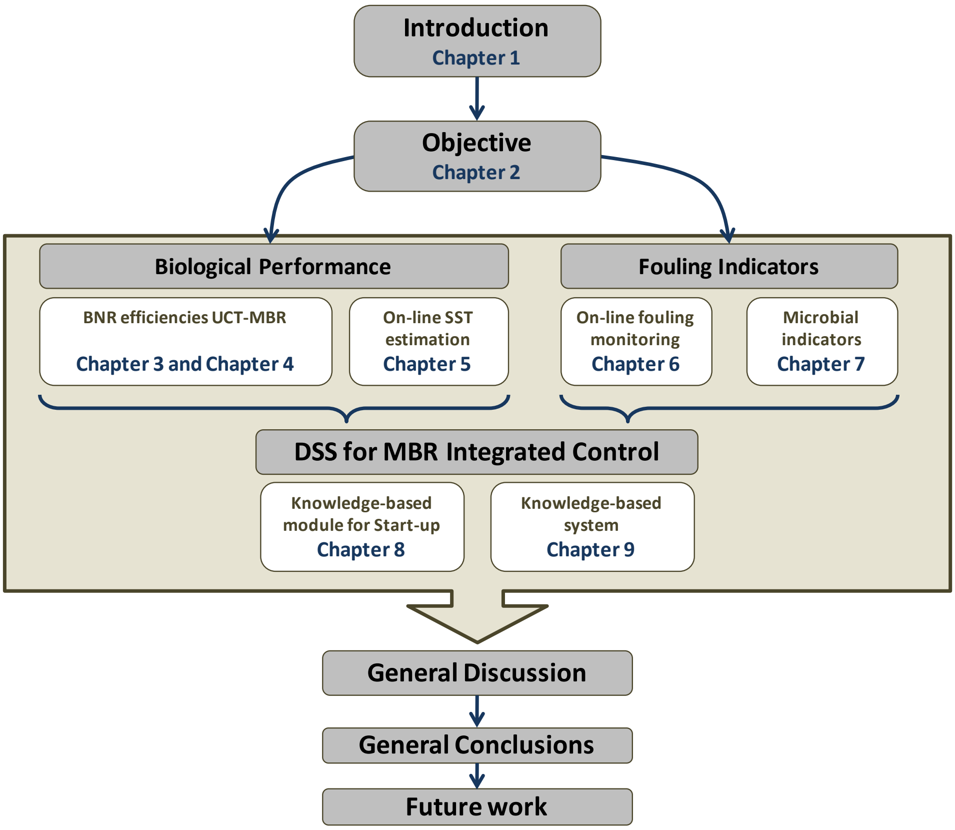

Figure 2.1 Thesis Road Map.

OUTPUTS

This section presents the achieved outputs as thesis chapters

Block I

Biological performance using MBR

*This first block presents the validation of the operational conditions using an MBR (**Chapter 3 and Chapter 4**), and the validation of a generic Kalman observer for the online estimation of solids concentration (**Chapter 5**).*

Chapter 3

Optimization of BNR in a pilot plant UCT-MBR treating municipal wastewater during start-up

The objective of this chapter was to ***evaluate*** *the operational conditions for BNR, modelling the system during* ***unsteady state*** *periods, such as start-up periods.*

H. Moncús, J. Sipma, G. Ferrero, J. Comas, I. Rodriguez-Roda. "Optimization of biological nutrient removal in a pilot plant UCT-MBR treating municipal wastewater during start-up". *Desalination*. Vol. 250, issue 2 (15 January 2010) : p. 592-597

Available online 9 October 2009

http://dx.doi.org/10.1016/j.desal.2009.09.030

http://www.sciencedirect.com/science/article/pii/S0011916409010030

Abstract

This study shows that an MBR pilot plant with UCT configuration is able to obtain high nutrient removal efficiency already during start-up. The biological nutrient removal (BNR) efficiencies significantly increased towards the end of the experimental run, achieving a COD removal efficiency exceeding 94% and N removal efficiency in the range of 89 to 93%. P removal efficiencies in the range of 80 to 92% have been obtained. During the experimental period (4 months) the evolution of the activity of polyphosphate-accumulating organisms, obtained from $P_{release}$ and P_{uptake} rates, showed a small increase in the activity of polyphosphate-accumulating organisms (PAOs) and denitrifying polyphosphate-accumulating organisms (DPAOs). The specific phosphate accumulation at the end of the experimental run amounted to 8.0 mg P g^{-1}VSS h^{-1} and 3.29 mg P g^{-1}VSS h^{-1}, for the PAOs and DPAOs respectively. Moreover, the DPAOs activity increased faster than PAOs activity, i.e. from 0.36 to 0.41 of phosphate uptake rate (PUR) ratio.

Keywords

- Biological nutrient removal (BNR);
- Enhanced biological phosphorous removal (EBPR);
- Membrane bioreactor (MBR);
- Polyphosphate-accumulating organisms (PAOs)

Chapter 4

Biological nutrient removal in a MBR treating municipal wastewater with special focus on biological phosphorus removal

*The objective of this chapter was to evaluate the **operational conditions** for BNR, monitoring the **phosphorus activities**.*

Hector Monclús, Jan Sipma, Giuliana Ferrero, Ignasi Rodriguez-Roda, Joaquim Comas. " Biological nutrient removal in an MBR treating municipal wastewater with special focus on biological phosphorus removal". *Bioresource Technology*. Vol. 101, issue 11 (June 2010) : p. 3984-3991

Received 27 October 2009. Revised 29 December 2009. Accepted 10 January 2010. Available online 5 February 2010.

http://dx.doi.org/10.1016/j.biortech.2010.01.038

http://www.sciencedirect.com/science/article/pii/S0960852410000957

Abstract

The performance of an MBR pilot plant for biological nutrient removal was evaluated during 210 days of operation. The set point values for the internal recycles were determined in advance with the use of an optimisation spreadsheet based on the ASM2d model to optimise the simultaneous removal of C, N and P. The biological nutrient removal (BNR) efficiencies were high from the start of operation with COD and N removal efficiencies of 92 ± 6% and 89 ± 7, respectively. During the course of the experiment P removal efficiencies increased and finally a P-removal efficiency of 92% was achieved. The activity of poly-phosphate accumulating organisms (PAOs) and denitrifying poly-phosphate accumulating organisms (DPAOs) increased and the specific phosphate accumulation rates after 150 days of operation amounted to 13.6 mg P g^{-1}VSS h^{-1} and 5.6 mg P g^{-1}VSS h^{-1}, for PAOs and DPAOs, respectively.

Keywords

- Biological nutrient removal (BNR);
- Enhanced biological phosphorus removal (EBPR);
- Membrane bioreactor (MBR);
- Poly-phosphate accumulating organisms (PAOs);
- UCT configuration

Chapter 5

On-line estimation of suspended solids in biological reactors of WWTPs using a Kalman observer

*This paper presents the design, development and validation of a generic **Kalman** observer for the **online estimation** of solids concentration in the tank reactors of WWTPs.*

S. Beltrán, I. Irizar, H. Monclús, I. Rodríguez-Roda and E. Ayesa. “On-line estimation of suspended solids in biological reactors of WWTPs using a Kalman observer”. *Water Science & Technology*. Vol. 60, issue 11 (2009) : p. 567-574

http://dx.doi.org/10.2166/wst.2009.302

http://www.iwaponline.com/wst/06003/wst060030567.htm

ABSTRACT

The total amount of solids in Wastewater Treatment Plants (WWTPs) and their distribution among the different elements and lines play a crucial role in the stability, performance and operational costs of the process. However, an accurate prediction of the evolution of solids concentration in the different elements of a WWTP is not a straightforward task. This paper presents the design, development and validation of a generic Kalman observer for the on-line estimation of solids concentration in the tank reactors of WWTPs. The proposed observer is based on the fact that the information about the evolution of the total amount of solids in the plant can be supplied by the available on-line Suspended Solids (SS) analysers, while their distribution can be simultaneously estimated from the hydraulic pattern of the plant. The proposed observer has been applied to the on-line estimation of SS in the reactors of a pilot-scale Membrane Bio-Reactor (MBR). The results obtained have shown that the experimental information supplied by a sole on-line SS analyser located in the first reactor of the pilot plant, in combination with updated information about internal flow rates data, has been able to give a reasonable estimation of the evolution of the SS concentration in all the tanks.

Keywords:

Kalman Filtering; mass balance; MBR; observers; on-line estimation; suspended solids

Block II

Fouling indicators

*The second block presents a study filtration in terms of fouling indicators (**Chapter 6**) and then a study to relate the fouling with the retention of viral and bacterial indicators (**Chapter 7**).*

Chapter 6

On-line fouling monitoring in submerged MBRs

Previous studies related with ***fouling*** *monitoring (Yoon et al., 1999; Le-Clech et al., 2006; Wang et al., 2008; Drews 2010; Zhang et al., 2010),* ***criticality*** *conditions (Mei et al., 2010; Monclús et al., 2010; Wei et al., 2010) and flux step method (Stephenson 2000; Le-Clech et al., 2003; van der Marel et al., 2009)* ***motivated*** *the development of a* ***fouling indicator*** *that detects, in real time, rapidly and in a highly sensitive way, the* ***filtration status*** *of the membrane.*

H. Monclús, G. Ferrero, G. Buttiglieri, J. Comas, I. Rodriguez-Roda. “Online monitoring of membrane fouling in submerged MBRs”. *Desalination.* Vol. 227, issues 1-3 (15 August 2011) : p. 414-419

Received 15 March 2011. Revised 11 April 2011. Accepted 21 April 2011. Available online 13 May 2011.

http://www.sciencedirect.com/science/article/pii/S0011916411003936

http://dx.doi.org/10.1016/j.desal.2011.04.055

Abstract

Membrane fouling is the most serious problem affecting membrane bioreactors (MBR). It decreases membrane permeability and consequently increases energy consumption. Various methods and techniques to measure fouling rates (FR) can be found in the literature, but few provide online data, and most are expensive or too invasive. The aim of this short communication is to present a new online method for monitoring and estimating the fouling in an MBR, based on the use of the derivative of the transmembrane pressure (TMP) per cycle, for which hourly and daily mean values can be obtained. This online method (FR per cycle) was experimentally evaluated at a lab-scale MBR plant, where fouling conditions were induced by the addition of a protein (albumin) and a polysaccharide (glucose). Finally, we compared the new method to standard methods, such as the flux-step method. Similar results for fouling rates were found, but the new method showed increased sensitivity. At the same time, the method seems to be useful in characterizing the nature of fouling.

Research Highlights

New online method for monitoring and estimating the fouling in an MBR. ► Based on the use of the derivative of the transmembrane pressure (TMP) per cycle. ► This methodology resulted more rapid and sensitive technique than TMP or permeability. ► Preliminary results illustrate that it can be used to characterize the type of fouling.

Keywords

- Fouling;
- Membrane bioreactor;
- Online signal;
- Slope;
- TMP

Chapter 7

Removal of microbial indicators from municipal wastewater by a membrane bioreactor

*The aim of this work was to study the **impact of removable and irremovable** membrane fouling on the **retention** of different viral and bacterial **indicators** in MBR, in order to gain information on some of the factors affecting the efficiency in **reclaiming water** by the membrane bioreactor technology.*

Elisabet Marti, Hector Monclús, Juan Jofre, Ignasi Rodriguez-Roda, Joaquim Comas, José Luis Balcázar. "Removal of microbial indicators from municipal wastewater by a membrane bioreactor (MBR)". *Bioresource Technology.* Vol. 102, issue 8 (April 2011) : p. 5004-5009

Received 28 September 2010. Revised 20 January 2011. Accepted 21 January 2011. Available online 31 January 2011.

http://dx.doi.org/10.1016/j.biortech.2011.01.068,

http://www.sciencedirect.com/science/article/pii/S0960852411001404

Abstract

The impact of removable and irremovable fouling on the retention of viral and bacterial indicators by the submerged microfiltration membrane in an MBR pilot plant was evaluated. *Escherichia coli*, sulphite-reducing *Clostridium* spores, somatic coliphages and F-specific RNA bacteriophages were used as indicators. The membrane demonstrated almost complete removal of *E. coli* and sulphite-reducing *Clostridium* spores. However, there was no correlation with membrane fouling. The phage removal varied in accordance with the irremovable fouling, rising from 2.6 to 5.6 $\log_{10}$ units as the irremovable fouling increased (measured by the change in the transmembrane pressure). In contrast, removable fouling did not have any effect on the retention of viruses by the membrane. These results indicate that irremovable membrane fouling may affect the removal efficiency of MBRs and, therefore, their capacity to ensure the required microbiological standards for the permeate achieved.

Research highlights

► Removal of bacterial indicators is not affected by the fouling. ► Removal of virus depends on the formation of irremovable fouling. ► The removable fouling does not show any effect in the virus retention. ► Both bacteriophages studied show the same retention by a membrane (0.4 µm)

Keywords

- Bacteriophage;
- Bacteria;
- Membrane bioreactor;
- Wastewater treatment

Block III

DSS for MBR integrated control and supervision

*The last block of this thesis presents some **outcomes** of the previous blocks to be **implemented** in the decision support system (DSS), achieving some **integrated control tools**.*

Chapter 8

Development and validation of Knowledge-based module for Start-up operation using FS membrane bioreactor

*This paper presents the development, implementation and validation of a **knowledge-based module** for the automatic start-up operation in MBRs using FS membrane. The module is based on a **decision tree** to build the knowledge base.*

Knowledge-based control module for start-up of flat sheet MBRs

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Abstract

In start-up periods low mixed liquor suspended solids concentration may lead to fouling phenomena and uncommon frequency of chemical cleanings using membrane bioreactors. A knowledge-based control module for the optimisation of start-up procedures in membrane bioreactors is presented and validated in this paper. The main objective of the control module is to accelerate the growth of suspended solids and the achievement of the design flux while minimising the fouling phenomenon during start-up periods. The module was validated in a pilot-scale membrane bioreactor with the University of Cape Town configuration and submerged flat sheet microfiltration membranes. The knowledge of the control system was represented as a decision tree before being implemented. A fully satisfactory start-up, both for the filtration and the biological phase, was obtained in 20 days, saving time and preserving the membrane integrity.

Keywords : Control System, Decision Support System, Flat Sheet, Fouling, Knowledge-based, Membrane Bioreactor, Start-up.

Symbols and abbreviations	
DSS	Decision support system
DT	Decision tree
FR	Fouling rate (dTMP/dT)
FS	Flat sheet
J	Flux
J_C	Critical flux
KB	Knowledge-based
MBR	Membrane bioreactor
MF	Microfiltration
MLSS	Mixed liquor suspended solids
TMP	Trans membrane pressure

1. INTRODUCTION

The membrane bioreactors (MBR) process provides many advantages: higher effluent quality with a lower footprint, reduced excess sludge production (Judd 2011), drastically enhanced elimination of pathogens and viruses (Arrojo *et al.*, 2005; Marti *et al.*, 2011), highly efficient nutrient removal (Monclús *et al.*, 2010b) and potential degradation of specific refractory pollutants (Sipma *et al.*, 2010). Moreover, as MBRs retain all suspended solids, the time needed to start a plant up is expected to be shorter than conventional activated sludge because of no biomass loss in the effluent (Stephenson 2000). One of the main limitations of MBRs, though, is the membrane fouling responsible for permeability decrease and the consequent increase in energy consumption (Le-Clech *et al.*, 2006; Judd 2011). It is a parameter to take into account under any operational condition of MBRs and even more during non-steady state periods like start-ups.

Despite their importance and frequency, non-steady state periods like start-ups are usually disregarded in wastewater treatment (Ferraris *et al.*, 2009). Gradual increases of influent concentration and significantly long start-up phases of up to 180 days and more to acclimate biological phases to new operative conditions, in particular for nitrifying biomass with low growth rate and low growth yield, may be necessary in specific cases with MBR (Van Zyl *et al.*, 2008; Xue *et al.*, 2009).

The start-up strategies can influence membrane fouling. In some cases, for example, the fouling rate increased faster during start-up without sludge inoculum than with it. Without it, in fact, the irreversible deposition of soluble compounds on the membrane surface and into membrane pores cause low filtration efficiencies, higher resistance values and a more rapid increase of irreversible fouling (di Bella *et al.*, 2010). Loading conditions can also affect the membrane performance. For example, during start-up periods, membrane fouling in MBRs fed with variable loadings was more significant than in MBRs with constant loading (Zhang *et al.*, 2010).

Besides, during a start-up period, if the mixed liquor suspended solids (MLSS) concentration is very low, the fouling phenomena can increase very fast and provoke an uncommon frequency of chemical cleanings (Le-Clech *et al.*, 2003). This effect is even more relevant in flat sheet (FS) membranes, which require a high MLSS concentration for effective aeration cleanings (relaxation periods (Judd 2011)). In this sense, during start-up periods the permeate flux is often kept low to avoid high fouling rates and the need for chemical cleanings until MLSS reach a certain value (preferably more than 5 g L^{-1}; Kubota, 2004). On the other hand, the flux should be kept as high as possible to increase the F/M and consequently stimulate the MLSS growth as fast as possible. This trade-off balance increases the complexity of FS MBR start-up periods, resulting in either long periods before reaching steady state/design operation or high fouling rates, and thus increasing operating costs. The effective management of this difficulty depends only on the experience of plant operators, if they have any.

An automatic control module, integrating all relevant information and knowledge to take the most adequate decision based on the process state, would certainly improve the economy and reliability of operation during start-up periods. A knowledge-based (KB) control module could accelerate the MLSS growth and facilitate obtaining the design flux while minimising fouling during start-up periods, reducing the need for chemical cleanings. Other knowledge-based systems have successfully demonstrated their potential to improve the management of wastewater treatment plants (Comas *et al.*, 2010; Ferrero *et al.*, 2011c).

The aim of this paper is to present the rationale of a knowledge-based control module for an automatic, consistent and rapid start-up. This module was initially developed and validated in a pilot-scale membrane bioreactor with the University of Cape Town (UCT) configuration and submerged FS microfiltration membranes, but it can be easily adapted to any MBR with FS membranes. Benefits of the proposed automatic knowledge-based system with respect to the current manual operation during start-up are also discussed.

2. MATERIALS AND METHODS

2.1. FS MBR pilot plant

The MBR pilot plant is equipped with a small settler and pre-screening module to prevent the entrance of large particles. The wastewater is obtained from the sewer that enters the full-scale wastewater treatment plant at Castell d´Aro (Catalonia, Spain) where the pilot plant is located. The wastewater, after passing a first coarse screen (10 cm), is pumped to the 1,000 L settler with the use of a peristaltic pump (Watson Marlow Bredel, Wilmington, USA). From this settler the wastewater is pumped to the anaerobic reactor with a positive displacement pump (Seepex, Bottrop, Germany) and passes through a filter with a nominal pore size of 2 mm to prevent large particles from entering the bioreactor and damaging the membranes. The pilot MBR treated raw municipal wastewater with an average C:N:P ratio of 100:11:0.9 (Monclús *et al.*, 2010a; Monclús *et al.*, 2010b; Sipma *et al.*, 2010).

The bioreactor with a total volume of 2.26 m^3 was designed according to the UCT configuration (Metcalf and Eddy 2003), i.e. the MBR consists of an anaerobic (14% of the total volume), an anoxic (14%) and an aerobic compartment (23%), that are ultimately followed by a compartment (49%) with submerged flat sheet membranes. The microfiltration (MF) membranes used have a total membrane area of 8 m^2 (LF10-Kubota, Kubota Corporation) and are characterised by a nominal pore size of 0.4 µm. More detailed pilot plant specifications can be obtained at **www.colmatar.es** or found in Monclús *et al.*, (2010b). The permeate is obtained by applying a vacuum pressure drop over the membranes using a second positive displacement pump, which is controlled by pressure transducers that measure the trans-membrane pressure (TMP).

3. RESULTS AND DISCUSSION

A preliminary start-up trial was assessed in the MBR pilot plant to acquire knowledge for the design of the KB control system. A manual operational system for start-up periods was applied and the pilot plant monitored for TMP, flux, MLSS concentration and fouling rates (FR). Real time data were collected from the remote control access and the results are presented in Figure 1. As can be observed, a high increase of MLSS was rapidly obtained, flux increased up to the designed flux of 25 LMH, but the TMP reached high values (up to 170 mbars) very quickly. Then the pilot plant was operating at permeability values that were too low so a chemical cleaning was needed to recover the initial membrane performance after only 20 days of operation.

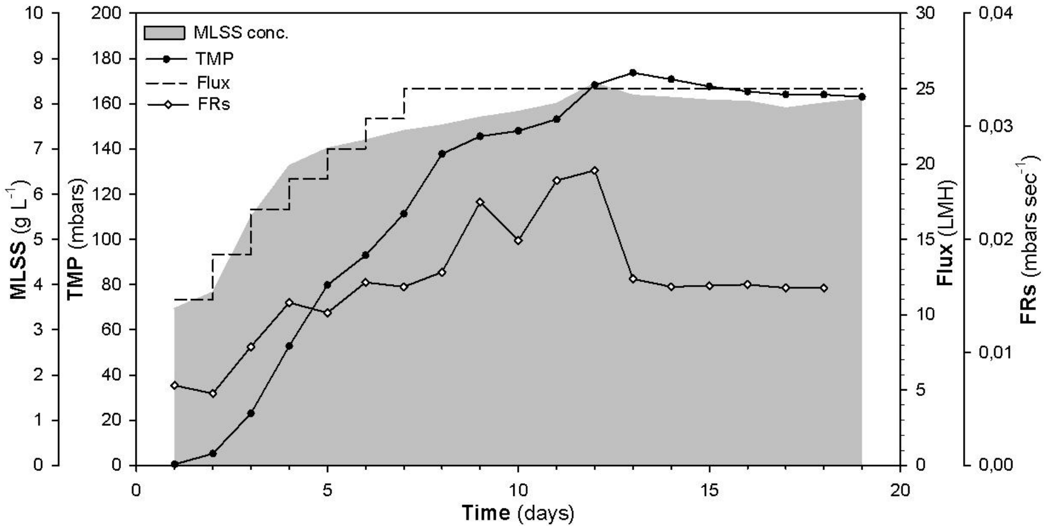

Figure 1. Monitoring of a manual operational mode start-up.

3.1. The automatic knowledge-based (KB) start-up module

The start-up KB module is in charge of processing data from the decision support system (DSS) lower level, regulating the control actions and monitoring the evolution of the process during the start-up period. The main objectives of this module are to achieve high inflows as fast as possible and the MLSS concentration advised by the manufacturers while, on the other hand, minimising the fouling phenomenon and reducing chemical cleanings and maintenance periods that would imply stopping the process.

The developed automatic KB control module for MBR start-ups is illustrated in a decision tree (DT) in Figure 2. It is composed of five different levels of discrimination. The entire tree is organised according to good, medium or bad conditions. If good conditions are verified a stronger control action is applied; if bad conditions are verified the applied control actions will be weaker to minimise the fouling phenomenon.

The first variable to be considered is the applied permeate flux (first level, Figure 2). When the flux is not the designed one (as it may happen in start-up conditions) the MLSS concentration will be checked (second level). Because the pilot plant operates with flat sheet membranes, high suspended solid concentrations are recommended by the provider. Hence, after flux, the MLSS concentration was considered to be the next influent variable determining which control action should be applied. According to the MLSS concentration, the increase of flux will be strong (over 6 g L^{-1}) or weak (between 6 and 3 g L^{-1}). Furthermore, the decision to modify the flux takes into consideration, on one hand, the actual state of the membrane (TMP, third level) and the fouling rates (FR, TMP slope per cycle, fourth level, (Monclús *et al.*, 2011)) and, on the other hand, the filterability of the sludge (fifth level, variable considered low when it is ≤10mL). When the FR is low (<0.0083 mbar sec^{-1}, (Monclús *et al.*, 2010c), then the proposed control action to be applied will be stronger because a safe membrane performance can be assumed. If the filterability is low, an addition of flocculant will be proposed.

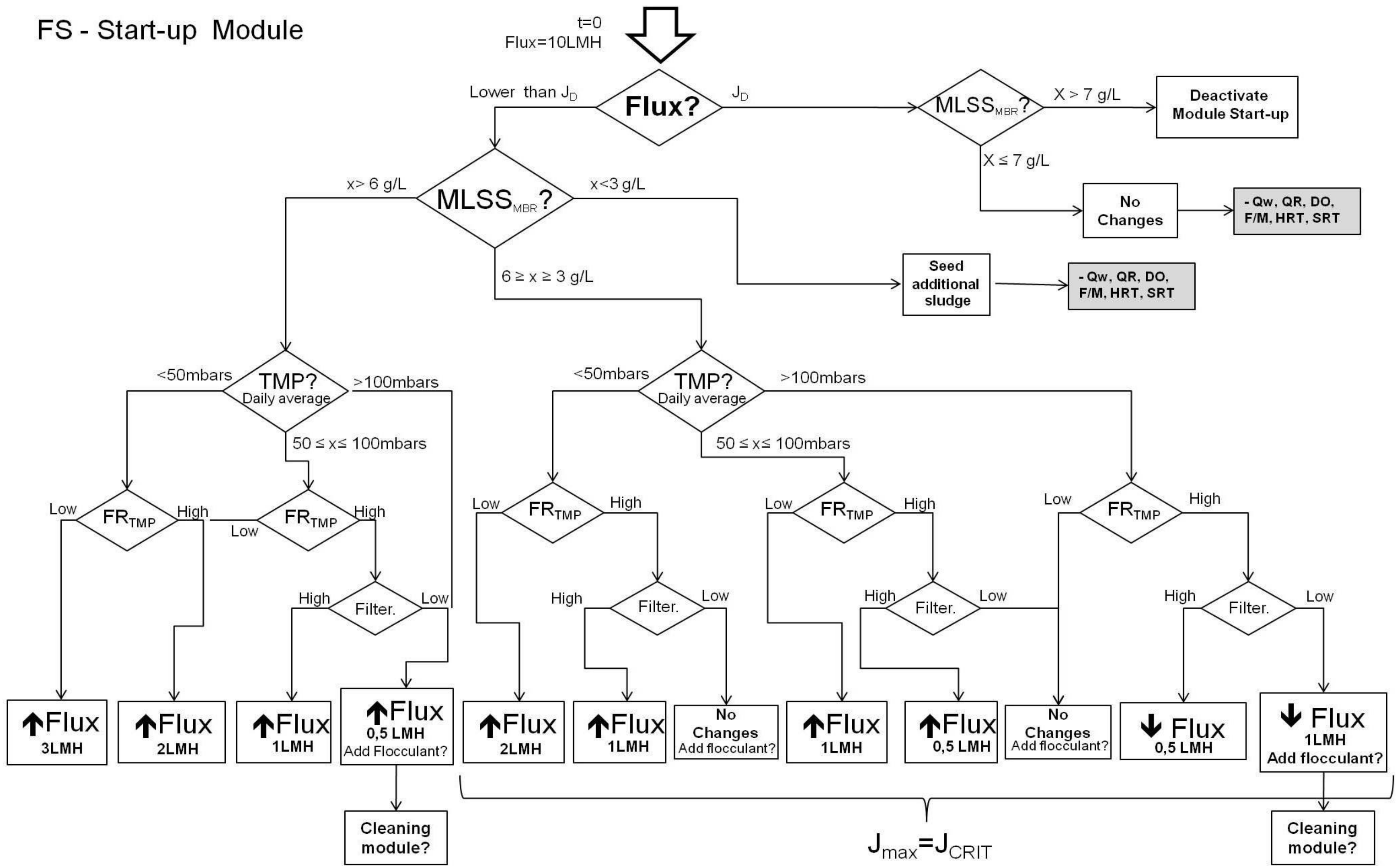

Figure 2. Decision tree to reduce decision-making time and to improve the consistency and quality of the decisions during a start-up period in a FS-MBR.

Sequential decisions will be automatically taken by the system until the designed flux and MLSS will be obtained, minimising potential negative effects on the membrane safety status. After three consecutive loops through the same decision branch, a loop counter will propose to check the biological conditions, taking into account the waste flow rate and the calibration of some sensors, and checking hydraulic retention time (HRT) and sludge retention time (SRT) to rule out any operation problems. Although the control actions proposed by the KB control module are applied once a day, the control system is also able to carry out hourly control actions using hourly averaged data.

The validated knowledge-based system for MBR start-up will be integrated in a decision support system (DSS) that is being developed for the remote control and integrated operation of MBRs (Comas *et al.*, 2010; Ferrero *et al.*, 2011b; Monclús *et al.*, 2011). The DSS is organised in a three-level architecture: the data acquisition and processing level, the automatic control level and the supervisory level. The lowest level is responsible for data acquisition and signal processing. The control level regulates all the actions of the automatic control loops for an integrated operation of MBR (control of aerobic DO, Kla in membranes, waste sludge, etc.). Finally, the knowledge-based supervisory level supervises the automatic control loops of both the biological and filtration processes through different modules. This level is composed of diverse knowledge-based modules, some of which have already been developed and validated (saving energy (Ferrero *et al.*, 2011a; Ferrero *et al.*, 2011b), biological nutrient removal optimisation (Monclús *et al.*, 2010a), online fouling monitoring (Monclús *et al.*, 2011) and operational problems (in development phase)). When a specific module is activated, it might adapt or change some control actions of the DSS intermediate level. Also, when the process is under *start-up mode,* other control modules, i.e. KB control for energy and chemical optimisation, are deactivated (Ferrero *et al.,* 2011c). This KB control for cost optimisation is only activated when the process performance regime is diagnosed as “favourable” by the DSS (which means that the process evolves according to previously defined values in the top level, and no other critical problems, malfunctioning, alarms and/or equipment failure affect the process).

The supervisory level regulates also the maximum flux to be applied in the plant. When the MLSS concentration is under 6 g L^{-1}, the critical flux (J_C, 21 LMH for the FS membranes as recommended by the producer) will be the maximum acceptable flux. When the daily average value of MLSS concentration, on the other hand, achieves a value over 6 g L^{-1}, the maximum flux would be increased till the designed flux (J_D, 25 LMH in the configuration). Moreover, if any variable indicates bad conditions (low filterability conditions, high FR or high TMP), some control actions will be considered, at the supervisory level, to recover the status of the filtration performance. For example, if TMP exceeds more than 140 mbars a recovery control action will be suggested; if TMP exceeds 170 mbars, a recovery control action will be indicated as necessary.

3.2. Validation of the knowledge-based control module for start-up periods

In order to validate the KB module described in the previous paragraph, it was applied to a FS -MBR. The automatic start-up module was put into operation soon after the sludge inoculum was added to the pilot plant. Figure 3 presents the performance and evolution of different parameters (flux, TMP, FR and MLSS concentration). TMP values increased until day 6 when a 21 LMH flux (J_C) was achieved. Five consecutive days, working at 21 LMH, were then necessary to achieve a higher concentration of MLSS. The flux could then be increased in two steps up to 25 LMH (from day 12) due to the good conditions of the process, a high MLSS concentration, a low TMP, a low FR and high filterability. It should be mentioned that when a high MLSS concentration (~7 g L^{-1}) was achieved, the TMP and FR started to stabilise. In Figure 3, in fact, it is possible to observe that from day 13 the TMP was stable, in the range 79-90 mbars, and after a few days the same tendency was observed for FR, most likely indicating that a steady state filtration status had been achieved.

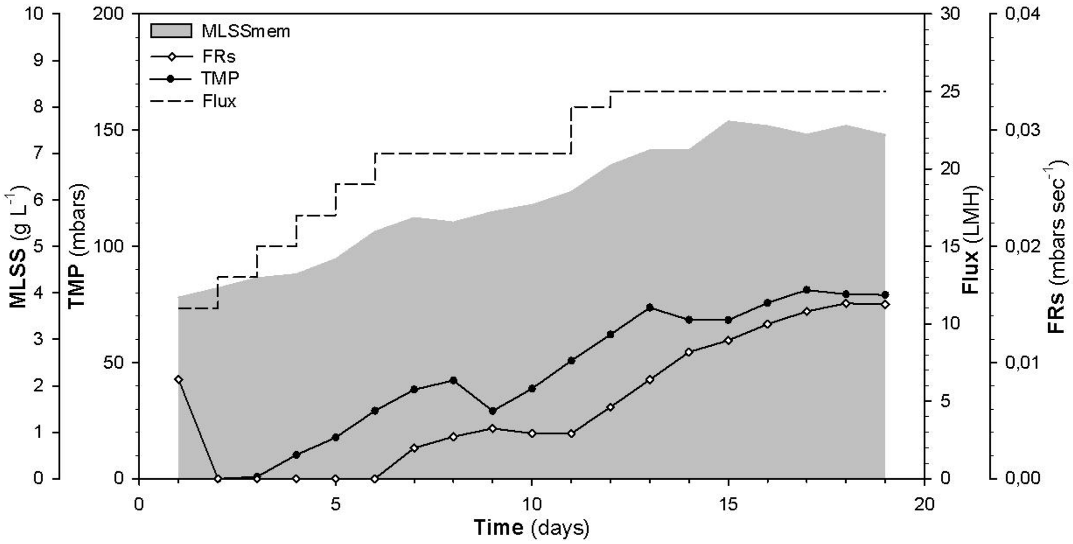

Figure 3. Start-up monitoring with the developed decision tree.

To stimulate biomass growth, the waste flow rate was progressively increased day after day and, even if the evolution of the SRT was not measured during the start-up, after 20 days the automatic control action for biological nutrient removal (Monclús *et al.*, 2010b) proposed to activate the waste to achieve 25 days as a SRT. It can be concluded, hence, that a very satisfactory nutrient removal was also achieved.

This automatic module was built for start-up periods, but it is a valuable and flexible tool that can be adapted to other non-steady state periods, e.g. a decrease in MLSS concentration in the membranes' tanks due to operational problems (such as problems with the MLSS due to waste pump or external recirculation malfunctioning) or when the filtration process is not stable.

The range of all variables can be customised according to the specific characteristics for different plant configurations, operational conditions and also membrane type (i.e. hollow fibre, multi-tubular or side-stream modules).

To preserve the membrane integrity, a fast increase of MLSS and a limited increase of TMP and FR were obtained while applying a fully automatic start-up system. It can therefore be concluded that this test verified the accuracy and consistency of the knowledge of the KB control module.

4. CONCLUSIONS

An automatic knowledge-based control module has been developed as a tool to control and minimise the fouling in MBRs during non-steady state conditions, such as start-up periods. Several variables were taken into account (flux, TMP, FR and MLSS concentration).

This KB control module was successfully validated in a FS MBR pilot plant with FS membranes. Improved quality decisions were taken with respect to a manual operational model and, on the base of the integration of multiple variables, an automatic, consistent and rapid start-up was obtained in 20 days. The module allowed a fast start-up, minimised the fouling phenomena (with stable TMP and FR) to preserve the membrane integrity and, at the same time, obtained a rapid MLSS growth and satisfactory nutrient removal. It can also be coherently integrated in a wider DSS for integrated control of MBR.

5. ACKNOWLEDGEMENTS

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Chapter 9

Knowledge-based system for automatic MBR control

*This paper presents the design and development of the **knowledge-based architecture**. Furthermore, the control system is fully described with some brief explanation about the different automatic modules installed on the top level of the **hierarchical architecture***

J. Comas, E. Meabe, L. Sancho, G. Ferrero, J. Sipma, H. Monclús and I. Rodriguez-Roda. "Knowledge-based system for automatic MBR control". *Water Science & Technology.* Vol. 62, issue 12 (2010) : p. 2829-2836

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http://www.iwaponline.com/wst/06212/wst062122829.htm

ABSTRACT

MBR technology is currently challenging traditional wastewater treatment systems and is increasingly selected for WWTP upgrading. MBR systems typically are constructed on a smaller footprint, and provide superior treated water quality. However, the main drawback of MBR technology is that the permeability of membranes declines during filtration due to membrane fouling, which for a large part causes the high aeration requirements of an MBR to counteract this fouling phenomenon. Due to the complex and still unknown mechanisms of membrane fouling it is neither possible to describe clearly its development by means of a deterministic model, nor to control it with a purely mathematical law. Consequently the majority of MBR applications are controlled in an "open-loop" way i.e. with predefined and fixed air scour and filtration/relaxation or backwashing cycles, and scheduled inline or offline chemical cleaning as a preventive measure, without taking into account the real needs of membrane cleaning based on its filtration performance. However, existing theoretical and empirical knowledge about potential cause-effect relations between a number of factors (influent characteristics, biomass characteristics and operational conditions) and MBR operation can be used to build a knowledge-based decision support system (KB-DSS) for the automatic control of MBRs. This KB-DSS contains a knowledge-based control module, which, based on real time comparison of the current permeability trend with "reference trends", aims at optimizing the operation and energy costs and decreasing fouling rates. In practice the automatic control system proposed regulates the set points of the key operational variables controlled in MBR systems (permeate flux, relaxation and backwash times, backwash flows and times, aeration flow rates, chemical cleaning frequency, waste sludge flow rate and recycle flow rates) and identifies its optimal value. This paper describes the concepts and the 3-level architecture of the knowledge-based DSS and details the knowledge-based control module. Preliminary results of the application of the control module to regulate the air flow rate of an MBR working with variable flux demonstrates the usefulness of this approach.

Keywords: automatic control; energy saving; fouling; knowledge-based; membrane bioreactors

Chapter 10

Results, discussion and future perspectives

This chapter provides a summary and general discussion of the results followed by the future perspectives.

10.1 Summary of the results

All the studies developed through this thesis relate to the different aspects of the MBR integrated control listed below:

- Nutrient removal (**Chapter 3 and 4**)
- Suspended solids estimation (**Chapter 5**)
- Fouling monitoring (**Chapter 6**)
- Water reuse quality (**Chapter 7**)
- Start-up operation (**Chapter 8**)

Each study has also allowed knowledge to be extracted from the results to complement the DSS for the integrated control of MBRs. In the following sections, the main goals achieved are described.

10.1.1 Nutrient removal

The main goals of **Chapter 3 and 4** were to find and validate the operational conditions applied in the UCT-MBR plant during unsteady state (such as the start-up period) and steady state conditions.

Two different start-up periods, and more than 200 consecutive days, permitted the operational conditions for the BNR to be validated as optimal ones and high nutrient removal efficiencies, in both cases (start-up and steady state), to be achieved. Since MLSS are different than CAS in MBRs, DO, recycle and waste flow rates have to be optimised. An optimisation spreadsheet together with the ASM2d model led to the current operational conditions, which are summarised in Table 10.1.

Table 10.1 Operational conditions validated in an UCT-MBR

Parameter	Units	Value
Anaerobic recirculation	% of the inflow	129
Anoxic recirculation	% of the inflow	92
External recycle	% of the inflow	136
Wastage pump	% of the inflow	1.8
DO aerobic set point	$mg \cdot L^{-1}$	1.5

The operational conditions achieved present a different percentage of recycles compared to CAS. Working with a low percentage of recycle flow decreases the energy consumption for the pumping requirements and increases the residence time for the different conditions, such as anaerobic and anoxic. Higher anaerobic HRT stimulates high phosphorous activity and achieves, in a few days, high phosphorous removal efficiencies. Working with a UCT configuration also allowed good C and N removal efficiencies to be achieved.

Computational rules to automatically calculate the recirculation flows or any kind of operational parameters according to the current flux applied have been implemented to work on variable permeate fluxes, allowing that other control modules change the permeate flux without changes on the BNR removal efficiencies during more than 500 days.

However, some studies are still necessary to complement the DSS with the required knowledge to adapt all the operational conditions (recycles flows, DO, sludge waste flow, SRT, HRT) in real time, taking into account both the nutrient removal efficiencies and the filtration performances.

10.1.2 On-line suspended solids estimation

The primary objective of **Chapter 5** was to validate a Kalman observer as an on-line estimation of SS in an MBR plant. The MLSS concentration plays an important role, not only related to the BNR efficiencies, but also directly related to the filtration performance (Le-Clech *et al*., 2006; Meng *et al*., 2009), thus it is very important to know the MLSS concentration in real time.

An on-line estimation of solids concentration was designed, developed and then validated in the UCT MBR pilot plant through different short-term experiments.

The combination of both kinds of measurements, the on-line MLSS measurements at some points and all the independent flow rate measurements, can supply enough information to dynamically estimate both the evolution of the total suspended solids in the plant and their distribution among the different tanks or unit-process elements.

The proposed approach can also be extended to new "software sensors" capable of simultaneously estimating all the internal flow rates and solids concentrations within the process, facilitating the further development of more accurate dynamic mass balances or new procedures for fault detection or data reconciliation. Moreover, the solids estimation in the membrane tank will permit its development and implementation into the DSS to minimise its changes and/or to optimise the filtration cycles.

10.1.3 Fouling monitoring

There is a need for some fouling indicators to monitor the filtration performance and its fouling propensity online. For this reason in this study a new online method was proposed for monitoring and estimating membrane fouling in an MBR. A lab-scale MBR was used where fouling conditions were induced by external additions.

This study was based on the TMP slope, averaged per cycles, as a fouling indicator. This measure, combined with a measure of the TMP, enables operators to know, in each moment, if the membranes are working under or over critical conditions. As a result, it is possible to know the propensity of the membrane to become fouled in any conditions.

Chapter 6 presented the development, implementation and validation in a pilot plant of this new fouling indicator.

This fouling indicator complements the **supervision level** of the DSS with a new module which is used as a warning sign to indicate the propensity of the membrane to foul or clog.

Current studies aim to validate this method as a general, easy and sensitive way to differentiate the type of fouling appearing in any membrane and plant.

10.1.4 Water Reuse Quality

Although it is clear that the permeate from an MBR is of higher quality than the CAS effluent, in terms of SS, it was still necessary to study the impact of the fouling (removable and irremovable) on the retention of viral and bacterial indicators.

This study was based on monitoring the fouling during long-term periods to achieve a percentage of irremovable fouling, and also during short-terms periods (during a cycle) to evaluate the removable fouling.

Experiments described in **Chapter 7** permitted a correlation between the fouling and the efficiency of some microbial indicators. The effluent quality seems to be even better when the filtration performance is in steady state so when the membrane presents a percentage of irremovable fouling. This is because the pore size distribution is reduced due to the pore blocking. These results are a very valuable addition to the knowledge of the removal efficiencies of microbial indicators.

Research carried out in **Chapter 6** and **Chapter 7** is able to complement the DSS in terms of fouling characterisation. The use of the derivative of the TMP per cycle together with the permeability monitoring allows the fouling typology to be characterised. Besides, the microbial indicators are well suited to corroborate these conclusions, and future research will focus on that.

10.1.5 Start-up operation

During a start-up period, the fouling phenomenon is a constant threat and can provoke infrequent chemical cleanings. The aim of this study was to develop and validate in a pilot plant a knowledge-based decision tree to facilitate and to automate the MBR operation during a start-up period, modifying process variables to stimulate, as fast as possible, the MLSS growth and minimise the fouling phenomenon.

This start-up decision tree integrates multiple variables related to both nutrient removal (Chapter 3 and Chapter 4) and filtration performance (Chapter 6). The decision tree automatically achieved, in only 20 days, the designed MLSS concentration and flux, thereby minimising the fouling phenomena.

Once the flux is modified, the BNR module (Section 10.1.1) regulates all the necessary flows for the optimal nutrient removal (Table 10.1).

10.1.6 Knowledge-based system for automatic MBR control

The different studies carried out during this thesis have enabled us to design and complement the different knowledge-based modules and levels of the DSS for the MBR integrated control, not only regarding filtration performance but also nutrient removal performance.

In **Chapter 9** the DSS was fully described and a hierarchical architecture (Figure 10.3) was proposed to observe the different connections between the different levels and modules developed.

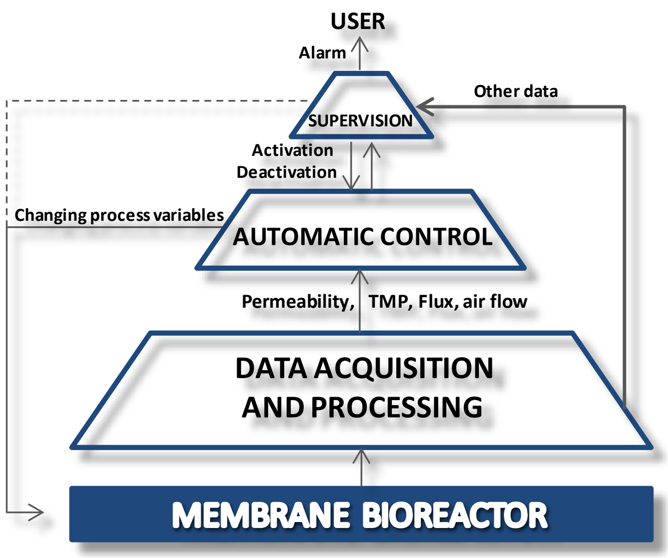

Figure 10.3. Hierarchical architecture of the expert system

The architecture of the DSS has been divided into three different levels. The *lowest level* is responsible for data gathering and signal processing, the *intermediate level* consists of an automatic control for different purposes, and finally, the *top level* contains a set of knowledge-based modules that monitor the performance of the plant to detect any operational problems or process alarms.

This top level (supervision level) stores all different automatic modules that can be launched when required. The automatic knowledge-based modules developed are listed below:

- Nutrient removal module (**Chapter 3 and 4**)
- Fouling indicator module (**Chapter 6**)
- Start-up knowledge-based module (**Chapter 8**)
- Save energy knowledge-based module (Ferrero *et al.*, 2011a; Ferrero *et al.*, 2011b; Ferrero *et al.*, 2011c)
- Operational problems module (**this thesis + future research**)
- Learning module (**this thesis + future research**)

These modules have allowed the UCT-MBR pilot plant to be operated automatically and remotely, and have provided the knowledge necessary for further developments and complements for the DSS.

Chapter 11
Conclusions

This chapter gives the main conclusions of this thesis .

11.1 Conclusions

The work carried out during this thesis has led to the following conclusions:

- The operational conditions applied in the MBR plant with UCT configuration efficiently removes C, N and P, achieving efficiencies of 96%, 89% and 88% respectively during start-up and at the end of the steady state period.

- The results presented illustrate that MBR technology allows similar or higher BNR rates to be obtained than with conventional activated sludge systems even when working with a high loading rate, and always with a much better effluent quality in terms of suspended solids.

- The combination of, the online SS measurements at some points and all the independent flow rate measurements is able to supply enough information to dynamically estimate both the evolution of the total suspended solids in the plant and their distribution among the different tanks or unit-process elements.

- The new method to monitor the online fouling rate (FR) has been validated as a better way to monitor the fouling in a UF MBR. Online measurement of the FR detected a fouling increase more easily and earlier with respect to the TMP and permeability monitoring alone.

- Bacterial indicators were successfully removed using MBR technology due to size exclusion without any correlation with the TMP evolution. On the other hand, the elimination of viruses was conditioned by the TMP, so it seems to depend on pore blocking, i.e. on irremovable fouling. On the contrary, removable fouling, i.e. cake layer formation, is not related to the elimination of viruses.

- The automatic supervision module for start-up phases using FS membranes was successfully validated and implemented in the DSS. The knowledge-based decision tree improved the quality of the decisions, making the start-up process more rapid and easier and integrating multiple variables.

- This module allowed a fast start-up, minimising the fouling phenomena (with stable TMP and FR), to preserve the membrane integrity and, at the same time, obtain rapid MLSS growth and satisfactory nutrient removal.

- All the studies carried out during the elaboration of this thesis have led to new knowledge about fouling and BNR in MBRs. It has all been organised in different knowledge-based modules within the DSS framework for MBR integrated control.

Chapter 12

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This chapter provides a full list of the references used through this entire thesis.

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Zhang, J., Zhou, J., Liu, Y. and Fane, A. G. (2010). "A comparison of membrane fouling under constant and variable organic loadings in submerge membrane bioreactors." Water Research **44**(18), 5407-5413.

Chapter 13 Annex

This chapter includes the curriculum vitae of the PhD candidate

CURRICULUM VITAE

Name: HECTOR MONCLÚS SALES
Date: 06/07/2011

Surnames: MONCLÚS SALES **Name:** HÈCTOR

D.N.I.: 46143303 **Date of birth:** 05/09/1979 **Gender:** Man

Actual professional status

Organization: Universitat de Girona
Faculty, School or Institute: FACULTAT DE CIÈNCIES
Dept./Sect./Str. Unit: ENGINYERIA QUÍMICA, AGRÀRIA I TECNOLOGIA AGROALIMENTÀRIA
Postal address: Laboratori d'Enginyeria Química i Ambiental (LEQUiA). Parc Científic i Tecnològic de la Universitat de Girona. Edifici Jaume Casademont. (Girona - 17003)
Phone number (Add number and extension): 0034659918752
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Professional category and starting date: PERSONAL INVESTIGADOR EN FORMACIÓ (MCYT) - 02/07/2007

Academic training

Bachelors Degree	Center	Date
Chemistry	Faculty of Sciences UdG	2006
Master on Water Science and Technology	Faculty of Sciences UdG	2008

Languages of Scientific Interest *(regular, Sufficient, Well)*

Language	Speak	Read	Write
Catalan	Well	Well	Well
Spanish	Well	Well	Well
English	Well	Well	Well

Fellowships

Colaborating Fellowship with the Laboratory of Chemical and Environmental Engineering (LEQUIA), Faculty of Sciences (UdG), (01/05/2006 - 01/11/2006).

Colaborating Fellowship with the Laboratory of Chemical and Environmental Engineering (LEQUIA), Faculty of Sciences (UdG) within the BTI program, (01/09/2006 -- 01/06/2007).

Predoctoral Fellowship of the Spanish ministry of Science and Education (MEC) (BES-2007-16286) within the COLMATAR PROJECT (DPI2006-15707-C02-01) AND COLMATAR + PROJECT (CTM2009-1-14742-C02-01), (02/07/2007 -- 01/07/2011)

Research topics

Short description, using keywords, about your main subject and current research topics

Line: Granular sludge formation using SBR technology
Center: Laboratori d'Enginyeria Química i Ambiental (LEQUiA) de la Universitat de Girona
Dates: 01/11/2006 -- 01/06/2007
Keywords: 001781 – Sequencing batch reactor (SBR) / 203036 - Aerobic Granular Sludge / 203037 – Biological nutrient removal (BNR)

Line: Study on the capability to treat landfill leachate with SBR technology
Center: Laboratori d'Enginyeria Química i Ambiental (LEQUiA) de la Universitat de Girona
Dates: 01/05/2006 -- 01/11/2006
Keywords: 001781 - Sequencing batch reactor (SBR) / 203038 – Landfill leachate / 203037 - Biological nutrient removal (BNR)

Line: Development, implementation and validation of a decision support system for the integrated control of membrane bioreactors to treat and reuse wastewater.
Center: Laboratori d'Enginyeria Química i Ambiental (LEQUiA) de la Universitat de Girona
Dates: since 01/07/2007 --
Keywords: 202494 - expert system / 203039 - Membrane Bioreactor (MBR) / 200765 - Wastewater Treatment / 200762 - Biological nutrient removal

Publications or Scientific-technical documents

Journal publications

Beltrán, S., Irizar, I., **Monclús, H.**, Rodriguez-Roda, I. and Ayesa, E. (2009). "On-line estimation of suspended solids in biological reactors of WWTPs using a Kalman observer." Water Science and Technology **60**(3), 567-574.

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Coma, M., Puig, S., **Monclús, H.**, Balaguer, M. D. and Colprim, J. (2010). "Effect of cycle changes on simultaneous biological nutrient removal in a sequencing batch reactor (SBR)." Environmental Technology **31**(3), 285-294.

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Marti, E., **Monclús, H.**, Jofre, J., Rodriguez-Roda, I., Comas, J. and Balcazar, J. L. (2011). "Removal of microbial indicators from municipal wastewater by a membrane bioreactor (MBR)." Bioresource Technology **102**(8), 5004-5009.

Monclús, H., Puig, S., Coma, M., Bosch, A., Balaguer, M. D. and Colprim, J. (2009). "Nitrogen removal from landfill leachate using the SBR technology." Environmental Technology **30**(3), 283-290.

Monclús, H., Sipma, J., Ferrero, G., Comas, J. and Rodriguez-Roda, I. (2010a). "Optimization of biological nutrient removal in a pilot plant UCT-MBR treating municipal wastewater during start-up." Desalination **250**(2), 592-597.

Monclús, H., Sipma, J., Ferrero, G., Rodriguez-Roda, I. and Comas, J. (2010b). "Biological nutrient removal in an MBR treating municipal wastewater with special focus on biological phosphorus removal." Bioresource Technology **101**(11), 3984-3991.

Monclús, H., Zacharias, S., Santos, A., Pidou, M. and Judd, S. (2010c). "Criticality of flux and aeration for a hollow fiber membrane bioreactor." Separation Science and Technology **45**(7), 956-961.

Monclús, H., Ferrero, G., Buttiglieri, G., Comas, J. and Rodriguez-Roda, I. (2011). "Online monitoring of membrane fouling in submerged MBR." Desalination **277**(1-3), 414-419.

Muñoz, J., **Monclús, H.**, Forrero, G., Plensa, M., Rovira, S., Comas, J. and Rodríguez-Roda, I. (2008). "Integrated membrane bioreactor control: For the elimination of nutrients in wastewater." Ingeniería Química **460**, 124-129.

Puig, S., Coma, M., **Monclús, H.**, van Loosdrecht, M. C. M., Colprim, J. and Balaguer, M. D. (2008). "Selection between alcohols and volatile fatty acids as external carbon sources for EBPR." Water Research **42**(3), 557-566.

Sipma, J., Osuna, B., Collado, N., **Monclús, H.**, Ferrero, G., Comas, J. and Rodriguez-Roda, I. (2010). "Comparison of removal of pharmaceuticals in MBR and activated sludge systems." Desalination **250**(2), 653-659.

Patents and Utilility Models

Inventor/s (signature): Rodriguez-Roda I., Comas J., Poch M., Ferrero G., **Monclús H.**, Sipma J., Clara P., Canals J. y Rovira S.
Title: Procedimiento automatizado de control en tiempo real de un biorreactor de membranas y sistema de control correspondiente
Application number: ES 2333837 **First priority country:** SPAIN **Date of priority:** 2010
Main institutions: VUDG - Universitat de Girona and OHL MEDIO AMBIENTE INIMA,S.A.U
Model: Patent **Patent code:** 200054 **Order:** 001

Research stays abroad (longer than 30 days)

Center: Centre for water research. Cranfield University
Place: Cranfield **Country:** UNITED KINGDOM **Year:** 2009 **Duration:** 03M
Issue: Membrane Bioreactor
Key: Ph.D. Student - Supervisor: Simon Judd

Center: Centre for water research. Cranfield University
Place: Cranfield **Country:** UNITED KINGDOM **Year:** 2010 **Duration:** 04M
Issue: Membrane Bioreactor
Key: Ph.D. Student - Supervisor: Simon Judd

Conference contributions

Monclús, H.; Sipma, J.; Plensa, M.; Ferrero, G.; Comas, J.; Rodriguez-Roda, I. (2008). Optimization of biological nutrient removal in a MBR treating urban wastewater. Platform presentation. Conference on Membranes in Drinking Water Production and Wastewater Treatment (MDIW2008). Toulouse (FRANCE).

Sipma, J.; **Monclús, H.**; Plensa, M.; Ferrero, G.; Comas, J.; Rodriguez-Roda, I. (2008). Microbial dynamics in a MBR and activated sludge plant with special emphasis on removal of refractory pollutants.

Poster. Conference on Membranes in Drinking Water Production and Wastewater Treatment (MDIW2008). Toulouse (FRANCE).

Plensa, M.; Sipma, J.; **Monclús, H**.; Ferrero, G.; Comas, J.; Rodriguez-Roda, I. (2008). Knowledge-based system for automatic MBR fouling control. Platform presentation. Conference on Membranes in Drinking Water Production and Wastewater Treatment (MDIW2008). Toulouse (FRANCE).

Rodriguez-Roda, I.; Plensa, M.; Sipma, J.; **Monclús, H.**; Comas, J.; Poch, M. (2008). Definition of the knowledge base for an optimal operation of the separation process in membrane bioreactors. Poster. Conference on Engineering with Membranes 2008. Algarve (PORTUGAL).

Rodriguez-Roda, I.; Comas, J.; **Monclús, H**.; Sipma, J.; Poch, M. (2008). Intelligent environmental decision support system for integrated operation of membrane bioreactors. Platform presentation. International Congress on Environmental Modelling and Software (iEMSs 2008). Barcelona (SPAIN)

Zelaskiewicz, A.; Sipma, J.; **Monclús, H**.; Rodriguez-Roda, I.; Comas, J. (2008). Biological degradation perspectives of pharmaceuticals in membrane bioreactors. Platform presentation. 7th Scientific Conference of Membranes and Membrane Processes in Environmental Protection. Ustron (POLAND).

Coma, M.; Puig, S.; **Monclús, H**.; Balaguer, M.D.; Colprim, J. (2008). Sludge granulation in an SBR for phosphorus removal. Poster. 4th Sequencing Batch Reactor Technology (SBR4) Conference. Roma (ITALY).

Monclús, H.; Puig, S.; Coma, M.; Balaguer, M.D.; Colprim, J. (2008). Treatment of high N loaded leachates using the SBR technology: Practical experiences. Poster. 4th Sequencing Batch Reactor Technology (SBR4) Conference. (**BEST POSTER AWARE**). Roma (ITALY).

Puig, S.; Coma, M.; **Monclús, H**.; van Loosdrecht, M.C.M.; Colprim, J.; Balaguer, M.D. (2008). Ethanol as a carbon source for biological nutrient removal from wastewaters. Platform presentation. 4th Sequencing Batch Reactor Technology (SBR4) Conference. Roma (ITALY).

Comas, J.; Rodriguez-Roda, I.; Sipma, J.; **Monclús, H**.; Ferrero, G. (2008). Sistema de ayuda a la decisión para el control de bioreactores de membranas. Platform presentation. Mesa Española de Tratamientos de Agua 2008 (META). Puerto de la Cruz (Tenerife) (SPAIN).

Monclús, H.; Ferro, G.; Sipma, J.; Ferrer, I.; Rodriguez-Roda, I.; Comas, J. (2009). BNR using a UCT-MBR treating municipal wastewater with special focus on EBPR monitoring by phosphorous activities. Platform presentation. 2nd IWA Specialised Conference. Nutrient Management in Wastewater Treatment Processes. Krakow (POLAND).

Ferrero, G.; **Monclús, H**.; Sipma, J.; Comas, J.; Rodriguez-Roda, I. (2009). Performance of an MBR pilot plant operated under variable fluxes. Poster. 5th IWA Specialised Membrane Technology Conference for Water & Wastewater Treatment. Beijing (CHINA).

Rodriguez-Roda, I.; Comas, J.; Clara, P.; Ferrero, G.; **Monclús, H**.; Sipma, J. (2009). Development of a Decision Support System for the operation and supervision of MBRs. Poster. 5th IWA Specialised Membrane Technology Conference for Water & Wastewater Treatment. Beijing (CHINA).

Comas, J.; Meabe, E.; Sancho, L.; Ferrero, G.; Sipma, J. **Monclús, H**.; Rodriguez-Roda, I. (2009). Knowledge-based system for automatic MBR control. Poster. 10th IWA Conference on Instrumentation, Control and Automation. Cairns (AUSTRALIA).

Beltrán, S.; Irizar, I.; **Monclús, H**.; Rodriguez-Roda, I.; Ayesa, E. (2009). On-line estimation of suspended solids in biological reactors of WWTPs using a Kalman observer. Platform presentation. 10th IWA Conference on Instrumentation, Control and Automation. Cairns (AUSTRALIA).

Monclús, H.; Ferrero, G.; Sipma, J.;Comas, J.; Rodriguez-Roda, I. (2009). Decision support system for MBR fouling control. Poster. Final MBR-Network Workshop. Berlin (GERMANY).

Gabarrón, S; **Monclús, H**.; Dalmau, M; Ferrero, G.; Rodriguez-Roda, I.; Comas, J. (2010). On-line control of aeration in a membrane bioreactor. Poster. International IWA Conference on Sustainable Solutions for Small Water and Wastewater Treatment Systems (S2SMALL 2010). Girona (SPAIN).

Monclús, H.; Ferrero, G.; Sipma, J.; Gabarrón, S; Rodriguez-Roda, I.; Comas, J. (2010). Comparison of MBR-UCT start-ups at different permeate fluxes. Platform presentation**.** International IWA

Conference on Sustainable Solutions for Small Water and Wastewater Treatment Systems (S2SMALL 2010). Girona (SPAIN).

Ferrer, I.; **Monclús, H**.; Gabarrón, S; Ferrero, G.; Comas, J.; Rodriguez-Roda, I. (2010). On-line estimation of fouling rates in MBRs altered by proteins and polysaccharides. Platform presentation. International IWA Conference on Sustainable Solutions for Small Water and Wastewater Treatment Systems (S2SMALL 2010). Girona (SPAIN).

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Monclús, H.; Ferrero, G.; Gabarron, S., Comas, J.; Rodriguez-Roda, I. (2010). Knowledge-base module for start-up optimization in flat-sheet membrane bioreactors. Poster. 7th International Membrane Science and Technology Conference (IMSTEC). Sydney (AUSTRALIA).

Buttiglieri, G., **Monclús, H**.; Ferrero, G.; Comas, J.; Rodriguez-Roda, I. (2010). On-line estimation of fouling in a membrane bioreactor. Poster. 7th International Membrane Science and Technology Conference (IMSTEC). Sydney (AUSTRALIA).

Dalmau, M., Gabarrón, S., **Monclús, H**., Rodríguez-Roda, I. and Comas, J. (2011). Simulation of biologic and filtration processes in a UCT-MBR pilot plant. Platform presentation on MBR ASIA 2011 Conference. Kuala Lumpur (Malasia).

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