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Optimization of full-scale membrane bioreactors for wastewater treatment through a model-based approach

S. Gabarrón [a,b], M. Dalmau [a], J. Porro [a], I. Rodriguez-Roda [a,b], J. Comas [a,*]

[a] LEQUIA, Institute of the Environment, University of Girona, Campus Montilivi, E-17071 Girona, Catalonia, Spain
[b] ICRA (Catalan Institute for Water Research), Scientific and Technological Park of the University of Girona, H_2O Building, c/ Emili Grahit 101, E-17003 Girona, Spain

HIGHLIGHTS

- Full-scale MBR optimization strategies were identified through scenario analysis.
- Model-based assessment was applied.
- Effluent quality, operational risks and costs were considered.
- Optimization strategies applied in a full-scale MBR achieved successful improvements.
- The proposed methodology could be applied to other chemical engineering processes.

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ABSTRACT

Despite the high number of advantages of membrane bioreactors (MBR), operational costs still remain as one of the main obstacles of this technology. In that sense, a full-scale MBR was studied in order to explore and identify viable optimization strategies for improving effluent quality and reducing operational costs through a model-based approach. Opportunities for optimization strategies, identified through the initial experimental phase, were focused on improving the nitrogen removal efficiencies and reducing the aeration energy costs through the aerobic DO set point and recirculation modifications. A mechanistic model was developed to reproduce the operation of the full-scale MBR and predict the effects of the optimization actions. Moreover, a qualitative risk model was also applied to ensure that the DO set point reduction did not negatively affect the microbiology of the activated sludge. The best viable control scenario was identified and then tested in the full-scale MBR. The results achieved maximum improvements on the nitrogen removal efficiencies of 27% and reduction on the aeration energy (7%) without affecting the sludge properties or the filtration performance. The model approached proved in this study and the optimization strategies identified can be generalized for municipal MBRs.

1. Introduction

Stricter effluent limits imposed on wastewater treatment plants over the past few decades have advanced treatment technology and increased the need for process optimization. Membrane bioreactors (MBRs), one of the more advanced treatment technologies utilized today, have become an excellent alternative to the conventional activated sludge (CAS) process for municipal wastewater treatment, especially when water reuse is needed [1]. This is due to the well-known advantages offered by MBR systems such as: lower footprint, lower sludge production, and higher effluent quality with nearly complete absence of pathogenic bacteria in the effluent [1].

However, operational costs still remain as one of the main obstacles of this technology [1], mainly due to the aeration [1,2]. Aeration is not only used for the membranes compartment, but also for the biological tanks, where it can also represent a significant amount of the operational costs, such as approximately 50% of the energy consumption of conventional activated sludge plants [3], and approximately 17% of MBR processes [4].

For membrane tanks, aeration is used for both to maintain in suspension the mixed liquor suspended solids, and to reduce fouling by scouring on the membrane surface [1,5]. This high amount of aeration used in MBRs provides a dissolved oxygen (DO) concentration in the membranes compartment reaching upwards of

* Corresponding author.
E-mail addresses: sara.gabarron@lequia.udg.cat, sgabarron@icra.cat (S. Gabarrón), montse.dalmau@lequia.udg.cat (M. Dalmau), jose.porro@lequia.udg.cat (J. Porro), irodriguezroda@icra.cat, ignasi@lequia.udg.cat (I. Rodriguez-Roda), quim@lequia.udg.cat (J. Comas).

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4 mg L^{-1} [6], which can negatively impact the nitrogen removal efficiency of the MBR system, especially when this high DO concentration is transferred to the head of the process in a high mixed liquor recycle flow, typically employed for denitrification. This high DO concentration can deteriorate the required anoxic conditions for denitrifying bacteria, which are facultative bacteria that energetically prefer oxygen versus nitrate as the terminal electron acceptor [7], hence limiting the reduction of nitrate.

Since most MBR plants are operated conservatively based upon manufacturers' recommendations, there has been limited research on full-scale MBR process optimization. Modeling and simulation tools are invaluable, in terms of time and effort needed to test different "what if" optimization strategies for improving effluent quality and reducing energy operational costs [8], as well as for providing insight on underlying mechanisms affecting process performance. Therefore, opportunities exist for the application of modeling and simulation for investigating full-scale MBR process optimization.

Activated sludge models are widely recognized for describing conventional activated sludge processes [9], and have been increasingly extended to include newer processes such as those from biofilm and MBR systems. There are few studies on the latter field related to energy optimization. On one hand, Dalmau et al. [10] presented the optimal biological and membrane aeration conditions for a proper nutrient removal, sludge characteristics and filtration performances, with up to 75% energy reduction.

On the other hand, a cost-evaluation and effluent quality analysis has been carried out on a UCT-MBR pilot plant in order to select the proper set points for various operational parameters [11]. Mannina and Cosenza [12] tested different energy saving scenarios accounting for all of the operational parameters involved in the filtration process. Verrecht et al. [13] modeled a small-scale decentralized MBR to both save energy saving and achieve better biological removal with a subsequently verification on the plant. All of them are only simulation, pilot or small scale studies. Notwithstanding the above, further research on model-based optimization of full-scale MBRs is needed.

The aim of this study is to identify viable optimization strategies for the operation of full-scale MBRs through a model-based approach. In order to reach this objective, the performance of a full-scale MBR has been thoroughly evaluated in order to determine specific control changes for improving the nutrient removal efficiencies and reducing the energy costs. A mechanistic model describing this full-scale MBR was used to help verify the underlying mechanisms impacting the treatment performance, and to evaluate the cost-effectiveness of the operational modifications. Finally, optimization strategies were implemented and evaluated in the full-scale MBR.

2. Materials and methods

2.1. Plant description

The full-scale WWTP is located in the Northeast of Spain, designed to treat 90,000 m^3 day^{-1}. It is a dual-stream facility with two parallel treatment lines: one with MBR technology (design flow of 15,000 m^3 day^{-1}), and the other with integrated fixed-film activated sludge (IFAS) (design flow of 75,000 m^3 day^{-1}). This study is limited to just the MBR process, and does not include the IFAS treatment. Influent from the primary settlers flows through 1 mm screen to the MBR, which contains two anoxic zones and two aerobic zones for denitrification and nitrification processes, respectively. Directly downstream, three membranes compartments are installed, with only two of them in operation at any given time (Fig. 1). The sludge is recirculated from the end of the aerobic tank to the beginning of the anoxic tank through the internal recirculation. Externally, the sludge from the membranes compartment is recirculated to the anoxic or aerobic tank, depending on the dissolved oxygen concentration of the activated sludge through an automatic control system. The MBR has an external recirculation, which has a DO sensor and depending on the DO concentration, flow is either recirculated to the anoxic tank (DO < 2 mg L^{-1}), or to the first aerobic tank (DO > 2 mg L^{-1}). This automatic control system was installed in order to prevent the anoxic tank conditions from being affected by the high DO concentration present in the membranes tanks, and avoid the deterioration of the denitrification process. The threshold DO value (2 mg L^{-1}) was determined by the MBR designers. The MBR operational parameters are described in Table 1. Chemical addition ($FeCl_3$) is required for the phosphorus removal. The regulatory effluent requirements for the WWTP are: Suspended solids (SS) < 35 mg L^{-1}; Biochemical oxygen demand (BOD_5) < 25 mg L^{-1}; Chemical oxygen demand (COD) < 125 mg L^{-1}; Total nitrogen < 10 mg L^{-1} and Total phosphorus < 1 mg L^{-1}.

2.2. Data collection and experimental campaigns

Influent and effluent data from historical data sets (specifically from October 2012 to May 2013) were analysed through weekly sample results (Table 2). In addition, two dedicated experimental campaigns were realized in order to characterize the influent and the effluent (permeate), and perform a detailed evaluation of the biological and filtration processes of the MBR. Specifically, samples taken from 12/5/2013 to 15/5/2013 and from 7/07/2013 to 10/7/2013 were collected every 2 h.

In all cases, the analysis carried out in the influent and effluent included chemical oxygen demand (COD), total Kjeldahl nitrogen (TKN), ammonia (NH_4^+–N), nitrates and nitrites (NO_3^-–N,NO_2^-–N), phosphates (PO_4^{3-}–P) and alkalinity following the standard methods procedures [14].

Sludge samples were analysed in terms of total suspended solids (TSS) following the APHA standard methods 2540D. Punctual daily measurements of extrapolymeric substances (EPS) and filterability were carried out during the two experimental campaigns. Bound EPS extraction from the activated sludge samples by cationic exchange resin was carried out according to Frølund et al. [15]. Protein concentration was measured by spectrophotometry using the Lowry method [16] modified by Peterson [17]. Polysaccharides content was analyzed using the Dubois method [18]. The dewaterability of the different mixed liquor samples was evaluated by measuring the capillary suction time (CST, Triton electronics Ltd., type 304 B) using the 6 mL cartridge. Filterability was determined using the protocol described by Kubota® filtering a 50 mL sample through a 2–4 μm pore disc filter (ALPL1244185) under gravity for five minutes.

MBR operational parameters were monitored during the experimental campaigns using online data (i.e. influent, permeate and waste flows, TMP and dissolved oxygen from the external recirculation, anoxic and aerated compartments).

2.3. Plant modelling methodology

The first step of the modelling methodology, model development, consisted of gathering all the available information from the plant in terms of design, operational, and historical data enabling the representation of the real plant. Once the model was created, calibration and validation was carried out using the first experimental campaign data. The model allowed different scenarios to be studied for possible operational parameter optimization by means of evaluating resulting effluent quality, costs and risk of microbiological problems related to bulking or foaming.