Water Research, Volume 45, Issue 6, March 2011, Pages 2181–2190

Accepted Manuscript

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PII: S0043-1354(11)00021-2

DOI: 10.1016/j.watres.2011.01.006

Reference: WR 8422

To appear in: *Water Research*

Received Date: 29 September 2010

Revised Date: 7 January 2011

Accepted Date: 10 January 2011

Please cite this article as: Maere, T., Verrecht, B., Moerenhout, S., Judd, S., Nopens, I. BSM-MBR: A Benchmark Simulation Model to Compare Control and Operational Strategies for Membrane Bioreactors, Water Research (2011), doi: 10.1016/j.watres.2011.01.006

- A benchmark simulation model for membrane bioreactors has been developed
- Operational and control strategies for MBRs can be dynamically assessed
- Predicted costs are realistic compared to full-scale MBRs
- Influent dynamics are very influential towards MBR performance
- Membrane aeration control shows significant potential in reducing operational costs

BSM-MBR: a Benchmark Simulation Model to Compare Control and Operational Strategies for Membrane Bioreactors

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Abstract

A benchmark simulation model for membrane bioreactors (BSM-MBR) was developed to evaluate operational and control strategies in terms of effluent quality and operational costs. The configuration of the existing BSM1 for conventional wastewater treatment plants was adapted using reactor volumes, pumped sludge flows and membrane filtration for the water-sludge separation. The BSM1 performance criteria were extended for an MBR taking into account additional pumping requirements for permeate production and aeration requirements for membrane fouling prevention. To incorporate the effects of elevated sludge concentrations on aeration efficiency and costs a dedicated aeration model was adopted. Steady-state and dynamic simulations revealed BSM-MBR, as expected, to out-perform BSM1 for effluent quality, mainly due to complete retention of solids and improved ammonium removal from extensive aeration combined with higher biomass levels. However, this was at the expense of significantly higher operational costs. A comparison with three large-scale MBRs showed BSM-MBR energy costs to be realistic. The membrane aeration costs for the open loop simulations were rather high, attributed to non-optimization of BSM-MBR. As proof of concept two closed loop simulations were run to demonstrate the usefulness of BSM-MBR for identifying control strategies to lower operational costs without compromising effluent quality.

Keywords

BSM; control; MBR; modelling; operational cost; optimization

LIST OF SYMBOLS AND ABBREVIATIONS

AE	aeration energy (kWh d^{-1})
$AE_{bioreactor}$	contribution to aeration energy by fine bubble aeration (kWh d^{-1})
$AE_{membrane}$	contribution to aeration energy by coarse bubble aeration (kWh d^{-1})
AE_{total}	total aeration energy (kWh d^{-1})
$AOTE$	actual oxygen transfer efficiency (%)
ASM	activated sludge model
ASM1	activated sludge model no. 1
BOD_5	5-day biological oxygen demand (g m^{-3})
BSM1	benchmark simulation model no. 1
BSM1_LT	long-term benchmark simulation model no. 1
BSM2	benchmark simulation model no. 2

BSM-MBR	benchmark simulation model for membrane bioreactors
C	actual oxygen concentration in the aeration tank (g m^{-3})
CAS	conventional activated sludge
COD	chemical oxygen demand (g m^{-3})
c_p	power factor (kWs kg^{-1})
$C^*(20)$	dissolved oxygen saturation concentration in clean water at 20 °C and 1 atm (g m^{-3})
c_{SI}	constant for unit conversion (-)
$C^*(T)$	dissolved oxygen saturation concentration for clean water at temperature T at sea level (g m^{-3})
$C^{*,av}(T)$	average dissolved oxygen saturation concentration for clean water in an aeration tank for a given temperature T at sea level (g m^{-3})
DO	dissolved oxygen concentration (g m^{-3})
e	blower efficiency (-)
EQI	effluent quality index (kg*PU* d^{-1})
F	correction factor for fouling of the air diffusers (1 for clean diffusers)
g	gravitational acceleration (m s^{-2})
h	depth of the aeration tank (m)
HRT	hydraulic retention time (h^{-1})
IQI	influent quality index (kg*PU* d^{-1})
LMH	unit for flux, i.e. l m^{-2} h^{-1}
MBR	membrane bioreactor
ME	mixing energy (kWh d^{-1})
n	air constant (-)
N	nitrogen (g m^{-3})

NO	nitrite plus nitrate nitrogen concentration (gN m^{-3})
$O_{A,m}$	mass percentage of oxygen in air (%)
$O_{A,v}$	volume percentage of oxygen in air (%)
OCI	operational cost index (d^{-1})
O_{out}	volume percentage of oxygen in air leaving the surface of the aeration tank (%)
OTR	oxygen transfer rate (g d^{-1})
P_{atm}	atmospheric pressure (Pa)
P_d	pressure at the bottom of the aeration tank (Pa)
PE	pumping energy (kWh d^{-1})
$PE_{effluent}$	contribution to pumping energy by effluent flow (kWh d^{-1})
PF_Q_x	pumping energy factor for sludge flow x (kWh m^{-3})
PE_{sludge}	contribution to pumping energy by all sludge flows (kWh d^{-1})
p_{in}	absolute inlet pressure (Pa)
p_{out}	absolute outlet pressure (Pa)
PU	pollution unit (-)
Q_A	airflow rate (Nm^3 d^{-1})
Q_e	effluent flow rate (m^3 d^{-1})
Q_i	influent flow rate (m^3 d^{-1})
$Q_{i,av}$	average influent flow rate (m^3 d^{-1})
$Q_{i,max}$	peak instantaneous influent flow rate (m^3 d^{-1})
Q_{int}	internal nitrate recirculation flow rate (m^3 d^{-1})
Q_r	return activated sludge flow rate (m^3 d^{-1})
Q_w	waste flow rate (m^3 d^{-1})
R	universal gas constant (J mol^{-1} K^{-1})

SAD_m	specific membrane aeration demand per unit of membrane area (Nm^3 h^{-1} m^2)
S_{ALK}	alkalinity concentration (molHCO_3^- m^{-3})
S_I	soluble inert organic material concentration (gCOD m^{-3})
S_{ND}	soluble biodegradable organic nitrogen concentration (gN m^{-3})
S_{NH}	ammonia plus ammonium nitrogen concentration (gN m^{-3})
$S_{NH,\ Limit\_violations}$	number of exceedances of effluent S_{NH} over 4 gN m^{-3} (-)
$S_{NH,\ 95}$	95^{th} percentile for effluent S_{NH} (gN m^{-3})
S_{NO}	nitrite plus nitrate nitrogen concentration (gN m^{-3})
S_O	dissolved oxygen concentration (g m^{-3})
$SOTE$	standard oxygen transfer efficiency (% m^{-1})
SP	sludge production for disposal (kgTSS d^{-1})
SP_{total}	total sludge production (kgTSS d^{-1})
SRT	sludge retention time (d^{-1})
S_S	soluble, readily biodegradable organic material concentration (gCOD m^{-3})
t	time (d)
T	temperature of the mixed liquor (°C)
T_{ev}	evaluation period (d)
T_{in}	absolute inlet temperature (K)
TKN	total Kjeldahl nitrogen concentration (g m^{-3})
TN	total nitrogen concentration (gN m^{-3})
$TN_{Limit\_violations}$	number of exceedances of effluent TN over 18 gN m^{-3} (-)
TN_{95}	95^{th} percentile for effluent TN (gN m^{-3})
TSS	total suspended solids concentration (g l^{-1})

TSS_{95}	95th percentile for effluent *TSS* (g l^{-1})
w	mass air flow rate (kg s^{-1})
WWTP	wastewater treatment plant
X_{BA}	autotrophic biomass concentration (g*COD* m^{-3})
X_{BH}	heterotrophic biomass concentration (g*COD* m^{-3})
X_I	particulate inert organic material concentration (g*COD* m^{-3})
X_{ND}	particulate biodegradable organic nitrogen concentration (g*N* m^{-3})
X_P	particulate organic material concentration from biomass decay (g*COD* m^{-3})
X_S	particulate, slowly biodegradable organic material concentration (g*COD* m^{-3})
y	aerator depth (m)
α	clean to process water correction factor (-)
β	salinity-surface tension correction factor (-)
ρ_A	density of air at standard conditions (g m^{-3})
ρ_{sludge}	the density of sludge (kg m^{-3})
φ	temperature correction factor for oxygen transfer (-)
ω	α factor exponent coefficient (-)

1. INTRODUCTION

The use of membrane bioreactors (MBRs) for wastewater treatment has increased significantly over the last 15 years due to technological advances and generally decreasing membrane costs. The high effluent quality offered compared to conventional activated sludge (CAS) systems makes MBRs especially suited for reuse (Judd, 2008). Their widespread application, however, is still limited by comparatively high life cycle costs over more conventional available options (Kinnear et al., 2010).

Marginal decreases in both capital and operational costs can be hugely influential in determining selection of MBRs, particularly at large scale.

For conventional wastewater treatment plants (WWTPs) and MBRs, mathematical models like the ASM family (Henze et al., 2000) are widely used for studying process behavior, system design and process optimization (Fenu et al., 2010a; Gernaey et al., 2004; Verrecht et al., 2010a). The latter has also led to the development of dedicated tools such as the COST/IWA Benchmark Simulation Model No. 1 (BSM1) (Copp, 2002; Jeppsson and Pons, 2004), which is a standardised simulation procedure for the design and evaluation of control strategies for conventional WWTPs in terms of effluent quality and operational costs, comprising a detailed description of plant layout, models, input and evaluation criteria. More recently, the importance of integrated control, plant-wide optimization and long-term evaluation was recognized within the wastewater treatment community and led to the development of BSM1_LT (Rosen et al., 2004) and BSM2 (Jeppsson et al., 2006; Nopens et al., 2010). The widespread use of BSM, with more than 300 publications based on BSM1/2, clearly indicates the usefulness of such a tool for the wastewater research community.

In this study, a dynamic benchmark simulation model for MBRs (BSM-MBR) is proposed as a platform to evaluate their operational and control strategies. Control systems have already been proven for optimizing operational costs and effluent quality for CAS plants (Olsson et al., 2005). The application of conventional control strategies for aeration, recirculation pumping, carbon addition, etc. to MBRs is, however, yet to be thoroughly investigated. In terms of quantifying operational costs for MBRs, thus far simple static spreadsheet models have been mainly adopted based on rules of thumb and steady-state operation (Verrecht et al., 2008; Yoon et al., 2004). Although useful, these models may lead to erroneous conclusions by not taking dynamic behavior and system configuration into account, and precluding the evaluation of process control. These aspects can all be explored using BSM-MBR.

2. MATERIALS AND METHODS

BSM-MBR is based on BSM1 (Alex et al., 2008; Copp, 2002). The modification of BSM1 to provide BSM-MBR was conducted using the modelling and simulation software WEST® (MOSTforWATER NV, Kortrijk, Belgium). Basic information on the BSM1/BSM-MBR influent files is given in Table 1. For BSM-MBR, the influent was assumed to already have passed pre-treatment, i.e. coarse screens, grit chamber, grease trap and fine sieves.

Insert Table 1: Flow-weighted average influent composition for BSM1 and BSM-MBR

2.1. Model configuration

Biokinetics As for BSM1, ASM1 (Henze et al., 2000) was used as biological process model for BSM-MBR. The BSM1 biokinetic parameter values were judged adequate for BSM-MBR; no consensus currently exists on updating the biokinetic values for MBRs due to contradictory literature findings (Fenu et al., 2010a), and the default parameter values have been shown to be sufficient (Verrecht et al., 2010b).

Membrane separation Separate filtration tanks were used, as is common in almost all submerged hollow fibre (HF) systems and many flat sheet (FS) ones, to provide flexibility in membrane operation and cleaning (Itokawa et al., 2008), notwithstanding increased pumping requirements. The characteristics and operation of the membrane modules were based on commercially available HF systems; minor modifications would be required for a flat sheet configuration to be represented.

All solids were assumed to be retained by the membrane. Fouling of the membranes was not modelled as such, since no consensus on its mechanisms has been reached. Coarse bubble aeration was incorporated in the model for fouling control so that its impact on biology and operational costs, assuming constant permeability, could be assessed. The design net flux was set to 20 l m^{-2} h^{-1} (LMH). Peak flows were assumed to incur a 100% increase in net flux to 40 LMH (Garcés et al., 2007). Backwashing and relaxation were not physically modelled.

71500 m^2 of membranes, divided over 8 separate 3.5m-high membrane tanks, were provided, enabling BSM-MBR to treat the peak instantaneous storm flow with one membrane tank out of service (worst-case scenario). 1500 m^3 of membrane tank volume was assumed to be required based on a packing density of 47.5 m^2 membrane area per m^3 tank volume, which is at the lower end of values reported in literature (Judd and Judd, 2010). A conservative specific membrane aeration demand (SAD_m) of 0.3 Nm^3 h^{-1} per m^2 of membrane area was chosen based on literature values for hollow fibre systems (Judd and Judd, 2010), resulting in a maximum of 21450 Nm^3 h^{-1} for coarse bubble aeration of the membranes. The target membrane tank total suspended solids (*TSS*) concentration was 10 g l^{-1}.

Tank sizing BSM-MBR was given a total bioreactor volume of 7500 m^3, including the membrane tanks, resulting in an *HRT* of 3 h at peak instantaneous storm flow and 9.8 h at average dry weather flow, which is within but at the lower end of values reported for large MBRs in Europe (Itokawa et al., 2008). Compared to BSM1 the total BSM-MBR volume was lower by 37.5%, while the bioreactor volume was actually 25% higher. As with BSM1, the total bioreactor volume was split into 5 zones: 2 anoxic zones followed by 3 aerobic zones, including the membrane tanks. The anoxic volume fraction was set to 40%. Thus, all zones were sized at 1500 m^3. To accommodate a worst-case scenario of 25% of the bioreactor volume being out of service, BSM-MBR was split up in 4 equal parallel lanes, as is actually the case for numerous full-scale WWTPs. As such, the actual volume of all 5m-high biological tanks was 375 m^3.

Sludge flows To keep the sludge concentration in the membrane tanks within reasonable limits and distribute it more evenly over the whole plant, sludge was recirculated from the membrane tanks to the first aerobic zone at 55338 m^3 d^{-1}, i.e. 3 times the average DWF. Sludge was also recirculated from the second aerobic zone to the first anoxic zone at the same rate to recycle nitrate. Waste sludge was taken from the membrane tank recirculation loop (200 m^3 d^{-1}) to maintain an *SRT* between 25 to 30 days as is common for MBRs (Itokawa et al., 2008). The general layout and flow scheme of BSM-MBR is shown in Fig. 1.

Insert Figure 1: BSM-MBR layout and flow scheme

Aeration In BSM1 the oxygen transfer rate (*OTR* - g d^{-1}) in the aerobic tanks is controlled by adapting the oxygen mass transfer coefficient. The aeration energy (*AE* – kWh d^{-1}) consumed is calculated from this coefficient according to an empirical formula. Using the equations of BSM1 for BSM-MBR would overlook the pivotal negative influence of elevated sludge concentrations, which is paramount in MBR systems, on oxygen transfer efficiency (Henkel et al., 2009). For this reason, and to allow differentiation between coarse and fine bubble aeration, a more fundamental and extensive aeration model was adopted, combining several literature findings (Germain et al., 2007; Judd and Judd, 2010; Stenstrom and Rosso, 2008; Tchobanoglous et al., 2003; Verrecht et al., 2008):

$$OTR = Q_A \cdot \rho_A \cdot O_{A,m} \cdot AOTE \qquad (1)$$

$$AOTE = SOTE \cdot y \cdot \frac{(\beta \cdot C^{*,av}(T) - C)}{C^{*}(20)} \cdot \varphi^{(T-20)} \cdot \alpha \cdot F$$

(2)

$$C^{*,av}(T) = \frac{1}{2} \cdot C^{*}(T) \cdot \left(\frac{P_d}{P_{atm}} + \frac{O_{out}}{O_{A,v}}\right) \quad (3)$$

$$\alpha = e^{-\omega \cdot TSS} \quad (4)$$

$$P_d = P_{atm} + \rho_{sludge} \cdot g \cdot h \quad (5)$$

$$O_{out} = \frac{100 \cdot O_{A,v} \cdot (1 - AOTE)}{(1 - O_{A,v} \cdot AOTE)}$$

(6)

The dissolved oxygen saturation concentration for clean water at temperature T at sea level ($C^{*}(T)$ - g m^{-3}) was calculated with the equation suggested by Benson and Krause (1984). The parameter values for Eq. 1 to 6 are given in Table 2. The chosen values may be regarded as mean values, or at least within the range of cited literature values. Parameter values for a specific MBR system could differ from the values reported here. For open loop operation (without control strategies implemented) a fine bubble aeration flow of 6500 Nm^3 h^{-1} was selected, of which 4250 Nm^3 h^{-1} for the first aerobic zone and the remainder for the second aerobic zone. The maximum possible fine bubble aeration was set at 7000 Nm^3 h^{-1} per zone, based on manufacturer data. The membrane tanks had no additional fine bubble aeration.

Insert Table 2: Oxygen transfer (top) and aeration energy (bottom) model parameter values

2.2. Evaluation criteria

The evaluation criteria of BSM1, these being the effluent quality index (*EQI* - kg*PU* d^{-1}) and the operational cost index (*OCI* - d^{-1}), were used for BSM-MBR, with the latter adapted with reference to energy demand in kWh d^{-1} from aeration (*AE*), pumping (*PE*) and mixing (*ME*).

Aeration energy The aeration energy for BSM-MBR was split into the contributions from fine bubble aeration in the bioreactors ($AE_{bioreactor}$) and coarse bubble aeration in the membrane unit ($AE_{membrane}$). Both were calculated by integration of the expression for power requirement for adiabatic compression (Tchobanoglous et al., 2003) over evaluation period T_{ev}:

$$AE = \frac{24}{T_{ev}} \cdot \int_{0}^{T_{ev}} \frac{w(t) \cdot R \cdot T_{in}}{c_{SI} \cdot n \cdot e} \cdot \left[\left(\frac{p_{out}}{p_{in}} \right)^{n} - 1 \right] \cdot dt = \frac{24}{T_{ev}} \cdot c_p \cdot \int_{0}^{T_{ev}} w(t) \cdot dt \qquad (7)$$

Eq. 7 combined with the parameter values in Table 2 provided a power consumption of 0.019 kWh Nm^{-3} of air for coarse bubble aeration and 0.025 kWh Nm^{-3} for fine bubble aeration, comparable with literature values (Verrecht et al., 2008).

Pumping energy As with BSM1, the *PE* for the sludge (PE_{sludge}) was derived from three pumped sludge flows: the internal nitrate recirculation flow (Q_{int} - m^3 d^{-1}), the waste flow (Q_w - m^3 d^{-1}) and the return activated sludge flow (Q_r - m^3 d^{-1}). A value of 0.0075 kWh m^{-3} was chosen for the pumping energy factors PF_Q_{int} and PF_Q_r, based on values for the MBR plants in Nordkanal and Varsseveld (De Wever et al., 2009). The value of 0.05 kWh m^{-3} for PF_Q_w was taken from BSM1.

Pumping relating to effluent (or permeate) production ($PE_{effluent}$) was calculated in the same way as for the sludge flows, with PF_Q_e set to 0.075 kWh m^{-3} based on values for Nordkanal, Varsseveld

(De Wever et al., 2009) and Schilde (Fenu et al., 2010b). Changes in PF_Q_e due to a varying filtration cycle, filtration flux and fouling behavior were ignored.

Mixing energy The total mixing energy (*ME* - kWh d^{-1}) comprised the energy used for mixing the anoxic, aerobic tanks and membrane tanks. The anoxic tanks were mixed constantly and required 0.008 kW mixing power per m^3 tank volume (Fenu et al., 2010b; Tchobanoglous et al., 2003), yielding a constant *ME* of 576 kWh d^{-1}. The threshold value for sufficient aeration for mixing was set at 165 $Nm^3\ h^{-1}$ for an aerobic tank and 120 $Nm^3\ h^{-1}$ for a membrane tank, based on a value of 2.2 $m^3\ h^{-1}$ per m^2 ground surface area (Water Environment Federation, 2009). Below the threshold additional mechanical mixing at 0.008 kW m^{-3} was assumed necessary.

2.3. Simulation procedure

Steady-state and dynamic simulations with BSM-MBR were performed in the same way as described for BSM1, i.e. steady-state simulation up to 10 times the sludge age followed by three weeks of dynamic dry weather and a last week, the evaluation period, of dynamic dry, rain or storm weather. Closed and open loop results refer to BSM-MBR simulations respectively with and without control strategies implemented. The full membrane and biological capacity was used in all simulations.

3. RESULTS AND DISCUSSION

3.1. Steady-state open loop evaluation.

The steady-state results for the open loop case of BSM-MBR are shown in Tables 3 and 4. The results in Table 3 show that BSM-MBR performs better in terms of effluent *TSS* and *COD* compared to BSM1, mostly because of the full retention of particulates by the membranes. In terms of *N* removal, it can be observed that superior nitrification is obtained in BSM-MBR. Effluent nitrate concentrations are however higher for BSM-MBR than BSM1 due to excessive aeration providing complete nitrification, while influent carbon for denitrification is limited with a *COD* to *TN* ratio of only 6.93 g*COD* gN^{-1}. Moreover, less nitrate and more oxygen is recycled back to the anoxic zone of BSM-MBR compared to BSM1, causing a reduced denitrification performance. The high *DO* levels in zones 3, 4 and 5 in Table 4 also indicate inhibited simultaneous nitrification-denitrification. The total *SRT* for BSM-MBR is 27.4 days, which is within the intended limits. The anoxic mass fraction amounts to only 31%, despite an anoxic volume fraction of 40%, due to the steep *TSS* gradient along the different reactor zones: 5.6 g l^{-1}, 7.4 g l^{-1} and 9.8 g l^{-1} for the anoxic, aerobic and membrane tanks respectively.

Insert Table 3: Comparison of BSM-MBR and BSM1 steady-state open loop effluent results

Insert Table 4: Steady-state open loop BSM-MBR results for reactor zones 1 to 5

3.2. Dynamic open loop evaluation

The dynamic dry, rain and storm weather results for the open loop case of BSM-MBR are shown in Table 5 and 6. From Table 5 it is clear that the use of membrane filtration instead of secondary clarification ameliorates adverse effects of rain and storm weather conditions on effluent quality, since sludge wash-out is not possible. The dynamic dry weather results in Table 5 are comparable to the steady-state results in Table 3 for BSM-MBR, but not for BSM1 in terms of S_{NH} and S_{NO}. Apparently the nitrification capacity of BSM1 is at times insufficient during dynamic simulations. BSM-MBR has 12.5% more aerobic volume compared to BSM1 and also carries more than two times the biological mass per unit volume. The excessive membrane aeration in BSM-MBR further ensures *DO* levels sufficiently high to maintain nitrification capacity during dynamic conditions.

Insert Table 5: Comparison of BSM-MBR and BSM1 dynamic open loop flow proportionally averaged effluent results for dry, rain and storm weather

The impact of influent dynamics on *TSS* and *DO* concentrations throughout BSM-MBR is clearly visible in Fig. 2. With every peak flow sludge is washed out the anoxic tanks towards the membrane tanks. The *TSS* concentrations in the first and second aerobic zone are stable (not shown). Having constant internal nitrate recirculation and return activated sludge flows is clearly insufficient for maintaining a stable sludge distribution over the plant at all times. The combination of a higher demand for oxygen during peak flows and less efficient aeration at high *TSS* induces high variability in the *DO* levels of the membrane tanks during dynamic simulations. The *DO* in the other aerobic zones is also highly variable. Even under normal dry weather conditions the *DO* in the second aerobic zone fluctuates from 0.25 mg l^{-1} to 6 mg l^{-1}. The former has, as mentioned before, little effect on effluent ammonium concentrations because of the excessive membrane aeration, the latter causes severe oxygen poisoning of the first anoxic zone.

Insert Figure 2: Impact of dry, rain and storm weather influent dynamics on TSS and DO in the membrane tanks, DO in the second aerobic zone and TSS in the first anoxic zone. The 2^{nd} and 3^{rd} day of the 7 day evaluation period are shown

BSM-MBR performs 51% (dry weather), 58% (rain weather) and 56% (storm weather) better than BSM1 in terms of *EQI* (Table 6), and no effluent limits are violated. Nonetheless, BSM-MBR effluent *TN* can be high at times (as indicated by TN_{95}) due to poor denitrification (as indicated by $S_{NH,\,95}$). Compared to the dry weather situation, the BSM-MBR *EQI* increases 15% and 6% for the rain and storm weather case respectively, whereas the corresponding BSM1 *EQI* figures are 34%

and 20%. BSM-MBR is thus more stable than BSM1 when subjected to varying influent conditions.

However, the superior effluent quality of BSM-MBR incurs a cost 61 - 69% higher than that of BSM1 depending on influent dynamics, according to the *OCI*. Other than for sludge disposal, all costs are increased significantly (140% for mixing, 306% for aeration and up to 580% for pumping). The higher mixing costs can be attributed to the larger anoxic volume to be mixed and the higher energy factor for mixing selected to incorporate the influence of elevated *TSS* on mixing. Care should be taken when comparing aeration costs between BSM1 and BSM-MBR, since their respective aeration models differ significantly. However, aeration costs can be expected to be higher for MBRs than CAS plants. 71% of the aeration costs for BSM-MBR are linked with the coarse bubble aeration for membrane fouling control, while it was calculated that the latter accounts for only 30 - 31% of oxygen transferred into the system with 2 - 3% of the total oxygen lost through the effluent. The elevated pumping energy costs for BSM-MBR can mostly be attributed to permeate production through membrane filtration. Also, more sludge is being pumped around in BSM-MBR than BSM1. The significant decrease in sludge production for disposal, 16 - 19%, can be explained by the more than three times longer *SRT* of BSM-MBR compared to BSM1 (Lubello et al., 2009).

Insert Table 6: Comparison of BSM-MBR and BSM1 dynamic open loop effluent quality and operational cost performance criteria for dry, rain and storm weather

3.3. Comparison with full-scale MBRs

The total specific energy requirement of modern, optimized large-scale MBR plants is reported as being in the range 0.6 - 1 kWh m^{-3} (Lesjean et al., 2009). Table 7 provides a breakdown of energy costs per m^3 of permeate for three large-scale MBR plants (Schilde, Varsseveld and Nordkanal) compared with the dry weather open loop results of BSM-MBR. Notwithstanding some energy costs being very plant specific, it seems that the BSM-MBR energy costs are comparable with those from full-scale plants. Only membrane aeration costs are consistently higher for BSM-MBR, since the membrane aeration was constantly applied to all membranes in the open loop simulations for BSM-MBR, whereas in reality membrane tanks are taken in and out of service depending on influent flow and membrane flux. The MBRs of Schilde, Varsseveld and Nordkanal are to some extent optimized, which BSM-MBR in its open loop form by definition is not.

Insert Table 7: Overview of total and specific energy costs for the MBRs of Schilde (Fenu et al., 2010b), Varsseveld (De Wever et al., 2009), Nordkanal (Brepols et al., 2010) and BSM-MBR under dry weather conditions

3.4. Closed loop performance

The impact of imposing a basic control and novel operational strategy for regulating aeration was studied for illustrative purposes.

DO control An aeration control scheme was implemented maintaining the *DO* concentration in the second aerobic zone at 1.5 mg l^{-1} using a PI controller to adjust the fine bubble aeration in both the first and second aerobic zone. Moreover, 50% more air was sent to the first than the second aerobic zone, since it receives a higher load, unless the maximum aeration capacity has been reached. The *DO* sensor and actuator performance was assumed to be ideal, i.e. without noise or delay. The proportional gain of the controller was tuned to 500 $Nm^3\ h^{-1}$ and the integral time to 0.002 d. The results in Table 8 show the proposed *DO* control strategy impact on effluent quality being marginally beneficial, if not the contrary, compared to the open loop case, with *EQI* decreasing 1 - 2% depending on the weather conditions, but the *TN* effluent limit also being violated in each case. The cost of fine bubble aeration decreased significantly, 8 - 12% compared with the open loop case, albeit with only a minor impact on overall *OCI* since the latter is dominated by sludge disposal and membrane aeration costs.

DO and SAD_m control Extending the former control scheme to link membrane aeration to flux, assuming this to have no major adverse effects on membrane fouling and sustainable flux (Garcés et al., 2007; Stone and Livingston, 2008), was tested. SAD_m was assumed to decrease linearly from 0.3 to 0.15 $Nm^3\ h^{-1}\ m^2$ with fluxes decreasing from 20 to 10 LMH. Beyond these limits SAD_m remained constant. Again, sensor and actuator performance was assumed ideal. The results in Table 8 show the SAD_m control scheme to have a minor effect on effluent quality, with *EQI* decreasing by 0 - 1% compared to the closed loop case with only *DO* control. The membrane aeration costs decrease by 42, 31 and 38% for the dry, rain and storm case respectively, while the fine bubble aeration costs increase marginally, i.e. 1 - 2%, to satisfy biological oxygen demand. Interestingly, diminishing membrane aeration has only minor effect on oxygen transfer since the latter still accounts for 27 - 29% of the oxygen transferred to the system (results not shown). The explanation lies in the lower DO levels obtained in the membrane tanks when membrane aeration is lowered. This increases the driving force for oxygen transfer, while, depending on the weather conditions, also 15 to 24% less oxygen is lost through the effluent. Compared to the open loop case, the overall *OCI* decreases by 13 - 17%. The results thus show large potential for saving energy by having proportional membrane aeration without compromising effluent quality. The latter may, however, be compromised when proportional membrane aeration is used combined with other operational and control strategies. Also, a thorough investigation of the technical feasibility and fouling control effectiveness of proportional membrane aeration is needed.

Insert Table 8: BSM-MBR dynamic closed loop effluent quality and operational cost performance criteria for dry, rain and storm weather

4. CONCLUSIONS

- A benchmark simulation model for MBRs (BSM-MBR) has been developed. The existing BSM1 for a conventional WWTP was used as starting point and updated in terms of reactor volumes, membrane filtration, aeration capacity and sludge flows. The BSM1 performance criteria were extended for an MBR taking into account additional pumping requirements for permeate production and aeration requirements for fouling suppression. A dedicated aeration model was used to incorporate the effects of elevated sludge concentrations on aeration efficiency and costs.
- Steady-state and dynamic open loop simulations revealed the effluent quality of BSM-MBR to be up to 58% better than that of BSM1, mainly thanks to the complete retention of solids and improved ammonium removal due to extensive aeration in combination with more biological mass. However, this was at the expense of significantly higher operational costs. Only the sludge disposal costs decreased for the BSM-MBR, due to the higher *SRT*.
- Impaired denitrification performance was evident due to oxygen poisoning of the first anoxic zone and a reduced anoxic mass fraction related to the steep *TSS* gradient along the bioreactor zones. Furthermore, the *TSS* gradient was found to be highly susceptible to influent flow dynamics, also having repercussions on aeration efficiency.
- A comparison with three large-scale MBRs showed BSM-MBR energy costs to be realistic. The membrane aeration costs for the open loop simulations were high due to the lack of optimization.
- Two closed loop simulations were run to show the potential of control strategies applied to BSM-MBR for diminishing operational costs by 13 - 17% depending on influent dynamics, without compromising effluent quality.

ACKNOWLEDGEMENTS

The authors want to thank Christoph Brepols (Erftverband) for his input on MBR costs and control strategies and Lorenzo Benedetti and Phuong Thu Pham (BIOMATH) for their assistance in modelling BSM-MBR. Thomas Maere is supported by the Institute for Encouragement of Innovation by means of Science and Technology in Flanders (IWT).

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Table 1: Flow-weighted average influent composition for BSM1 and BSM-MBR

Compound	Unit	Dry weather	Rain weather	Storm weather
S_I	g*COD* m^{-3}	30.00	25.96	28.03
S_S	g*COD* m^{-3}	69.50	60.13	64.93
X_I	g*COD* m^{-3}	51.20	44.30	51.92
X_S	g*COD* m^{-3}	202.32	175.05	193.32
X_{BH}	g*COD* m^{-3}	28.17	24.37	27.25
S_{NH}	g*N* m^{-3}	31.56	27.30	29.48
S_{ND}	g*N* m^{-3}	6.95	6.01	6.49
X_{ND}	g*N* m^{-3}	10.59	9.16	10.24
S_{ALK}	molHCO_3^- m^{-3}	7.00	7.00	7.00
$Q_{i,av}$	m^{-3} d^{-1}	18446.33	21319.75	19744.72
$Q_{i,max}$	m^{-3} d^{-1}	32180	52126	60000

Table 2: Oxygen transfer (top) and aeration energy (bottom) model parameter values

Parameter	Unit	Value
β	-	0.95
F	-	0.9[a] - 0.7[b]
g	$m\ s^{-2}$	9.81
$O_{A,m}$	%	23.2
$O_{A,v}$	%	21
P_{atm}	Pa	101325
ρ_A	$g\ m^{-3}$	1200
ρ_{sludge}	$kg\ m^{-3}$	1000
$SOTE$	$\%\ m^{-1}$	2[a] - 6[b]
T	°C	15
y	m	3.5[a] - 5[b]
φ	-	1.024
ω	-	0.05[a] - 0.083[b]
c_{SI}	-	29.7
e	-	0.5
n	-	0.283
p_{in}	Pa	101325
p_{out}	Pa	140660[a] - 155375[b]
R	$J\ mol^{-1}\ K^{-1}$	8.314
T_{in}	K	293.15

[a] Coarse bubble aeration, [b] Fine bubble aeration

Table 3: Comparison of BSM-MBR and BSM1 steady-state open loop effluent results

Compound	Unit	BSM1	BSM-MBR
S_I	g*COD* m^{-3}	30.00	30.00
S_S	g*COD* m^{-3}	0.89	0.67
X_I	g*COD* m^{-3}	4.39	0.00
X_S	g*COD* m^{-3}	0.19	0.00
X_{BH}	g*COD* m^{-3}	9.78	0.00
X_{BA}	g*COD* m^{-3}	0.57	0.00
X_P	g*COD* m^{-3}	1.73	0.00
S_O	g m^{-3}	0.49	8.11
S_{NO}	g*N* m^{-3}	10.42	12.57
S_{NH}	g*N* m^{-3}	1.73	0.07
S_{ND}	g*N* m^{-3}	0.69	0.58
X_{ND}	g*N* m^{-3}	0.01	0.00
S_{ALK}	molHCO$_3^-$ m^{-3}	4.13	3.85
TSS	g m^{-3}	12.50	0.00

Table 4: Steady-state open loop BSM-MBR results for reactor zones 1 to 5

Compound	**Unit**	**1**	**2**	**3**	**4**	**5**
S_I	gCOD m^{-3}	30.00	30.00	30.00	30.00	30.00
S_S	gCOD m^{-3}	2.25	1.31	0.85	0.77	0.67
X_I	gCOD m^{-3}	2678.62	2678.62	3554.43	3554.43	4722.18
X_S	gCOD m^{-3}	82.52	76.19	65.13	59.35	67.25
X_{BH}	gCOD m^{-3}	2699.15	2697.86	3573.19	3572.44	4739.59
X_{BA}	gCOD m^{-3}	233.30	233.07	311.13	311.33	413.41
X_P	gCOD m^{-3}	1781.17	1782.50	2372.10	2373.11	3155.87
S_O	g m^{-3}	0.01	0.00	2.46	2.19	8.11
S_{NO}	gN m^{-3}	4.09	1.48	10.08	11.54	12.57
S_{NH}	gN m^{-3}	8.57	9.22	1.58	0.33	0.07
S_{ND}	gN m^{-3}	1.08	0.68	0.65	0.63	0.58
X_{ND}	gN m^{-3}	5.38	5.16	4.73	4.40	5.14
S_{ALK}	molHCO_3^- m^{-3}	5.07	5.30	4.14	3.95	3.85
TSS	g m^{-3}	5606.08	5601.19	7406.98	7403.00	9823.72

Table 5: Comparison of BSM-MBR and BSM1 dynamic open loop flow proportionally averaged effluent results for dry, rain and storm weather

Compound	Unit	BSM1			BSM-MBR		
		Dry	**Rain**	**Storm**	**Dry**	**Rain**	**Storm**
S_I	gCOD m^{-3}	30.00	22.84	26.30	30.00	22.85	26.29
S_S	gCOD m^{-3}	0.97	1.13	1.11	0.70	0.72	0.74
X_I	gCOD m^{-3}	4.58	5.64	5.64	0.00	0.00	0.00
X_S	gCOD m^{-3}	0.22	0.34	0.32	0.00	0.00	0.00
X_{BH}	gCOD m^{-3}	10.22	12.86	11.88	0.00	0.00	0.00
X_{BA}	gCOD m^{-3}	0.54	0.64	0.59	0.00	0.00	0.00
X_P	gCOD m^{-3}	1.76	2.07	1.91	0.00	0.00	0.00
S_O	g m^{-3}	0.75	0.85	0.76	7.58	7.00	6.99
S_{NO}	gN m^{-3}	8.82	6.96	7.48	12.74	11.20	11.78
S_{NH}	gN m^{-3}	4.76	4.98	5.35	0.12	0.12	0.13
S_{ND}	gN m^{-3}	0.73	0.82	0.80	0.60	0.61	0.62
X_{ND}	gN m^{-3}	0.02	0.02	0.02	0.00	0.00	0.00
S_{ALK}	molHCO_3^- m^{-3}	4.46	5.14	4.87	3.85	4.49	4.19
TSS	g m^{-3}	12.99	16.16	15.26	0.00	0.00	0.00
TKN	gN m^{-3}	6.75	7.37	7.63	0.72	0.74	0.76
TN	gN m^{-3}	15.57	14.32	15.11	13.46	11.93	12.54
COD	g m^{-3}	48.30	45.52	47.76	30.70	23.58	27.03
BOD5	g m^{-3}	2.77	3.47	3.23	0.18	0.18	0.18
Q_e	m^3 d^{-1}	18061.33	23808.19	20658.08	18246.31	23993.17	20843.08

Table 6: Comparison of BSM-MBR and BSM1 dynamic open loop effluent quality and operational cost performance criteria for dry, rain and storm weather

Criterion	Unit	BSM1			BSM-MBR		
		Dry	Rain	Storm	Dry	Rain	Storm
IQI	kg*PU* d^{-1}	52081.40	52081.40	54061.50	52081.40	52081.40	54061.50
EQI	kg*PU* d^{-1}	6690.73	8936.23	8022.77	3286.54	3790.07	3499.88
TN_{95}	g*N* m^{-3}	18.54	17.79	18.72	16.83	15.75	16.74
$S_{NH, 95}$	g*N* m^{-3}	8.88	9.47	9.78	0.37	0.37	0.38
TSS_{95}	g m^{-3}	15.75	21.69	20.79	0.00	0.00	0.00
$TN_{Limit\_violations}$	-	5	3	4	0	0	0
(18 g*N* m^{-3})	% of time	8.18	4.32	8.48	0.00	0.00	0.00
$S_{NH, Limit\_violations}$	-	7	7	7	0	0	0
(4 g*N* m^{-3})	% of time	62.50	63.24	64.43	0.00	0.00	0.00
SP_{total}	kg*TSS* d^{-1}	2670.32	2737.14	2914.53	1961.12	1974.90	2166.26
- *SP*	kg*TSS* d^{-1}	2435.67	2352.32	2599.36	1961.12	1974.90	2166.26
AE	kWh d^{-1}	3341.39	3341.39	3341.39	13558.87	13558.87	13558.87
- $AE_{bioreactor}$	kWh d^{-1}	3341.39	3341.39	3341.39	3878.45	3878.45	3878.45
- $AE_{membrane}$	kWh d^{-1}	-	-	-	9680.42	9680.42	9680.42
PE	kWh d^{-1}	388.17	388.17	388.17	2208.54	2639.56	2403.30
- PE_{sludge}	kWh d^{-1}	388.17	388.17	388.17	840.07	840.07	840.07
- $PE_{effluent}$	kWh d^{-1}	-	-	-	1368.47	1799.49	1563.23
ME	kWh d^{-1}	240.00	240.00	240.00	576.00	576.00	576.00
OCI	d^{-1}	16147.92	15731.18	16966.34	26148.99	26648.91	27369.45

Table 7: Overview of total and specific energy costs for the MBRs of Schilde (Fenu et al., 2010b), Varsseveld (De Wever et al., 2009), Nordkanal (Brepols et al., 2010) and BSM-MBR under dry weather conditions

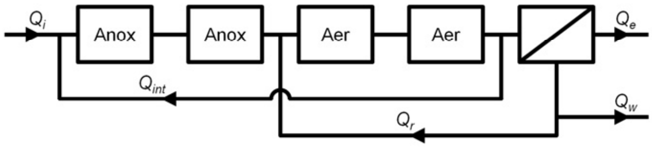
Energy cost (kWh m^{-3})	Schilde	Varsseveld	Nordkanal	BSM-MBR
ME	0.05	0.04	0.11	0.03
PE_{sludge}	0.10	0.11	0.01	0.05
$PE_{effluent}$	0.07	0.12	0.02	0.07
$AE_{bioreactor}$	0.07	0.24	0.11	0.21
$AE_{membrane}$	0.23	0.34	0.45	0.53
Total	0.52	0.85	0.71	0.90

Table 8: BSM-MBR dynamic closed loop effluent quality and operational cost performance criteria for dry, rain and storm weather

Criterion	**Unit**	***DO* control**			***DO* + *SAD$_m$* control**		
		Dry	**Rain**	**Storm**	**Dry**	**Rain**	**Storm**
IQI	kg*PU* d^{-1}	52081.40	52081.40	54061.50	52081.40	52081.40	54061.50
EQI	kg*PU* d^{-1}	3224.22	3717.95	3461.05	3203.27	3702.66	3440.81
TN_{95}	g*N* m^{-3}	17.46	16.21	17.25	17.37	16.13	17.17
$S_{NH,95}$	g*N* m^{-3}	0.17	0.18	0.17	0.17	0.18	0.18
$TN_{Limit\_violations}$	-	4	1	4	4	1	4
(18 g*N* m^{-3})	% of time	0.03	0.01	0.03	0.02	0.01	0.02
SP	kg*TSS* d^{-1}	1961.17	1975.06	2166.11	1961.20	1975.07	2166.14
AE	kWh d^{-1}	13142.86	13106.08	13234.11	9122.00	10120.26	9584.75
- $AE_{bioreactor}$	kWh d^{-1}	3462.44	3425.66	3553.69	3525.63	3471.58	3612.54
- $AE_{membrane}$	kWh d^{-1}	9680.42	9680.42	9680.42	5596.38	6648.68	5972.21
PE	kWh d^{-1}	2208.55	2639.56	2403.30	2208.55	2639.56	2403.30
- PE_{sludge}	kWh d^{-1}	840.07	840.07	840.07	840.07	840.07	840.07
- $PE_{effluent}$	kWh d^{-1}	1368.48	1799.49	1563.23	1368.48	1799.49	1563.23
ME	kWh d^{-1}	576.00	576.00	576.00	576.00	576.00	576.00
OCI	d^{-1}	25733.28	26196.96	27043.97	21712.54	23211.16	23394.74

Figure 1: BSM-MBR layout and flow scheme

Figure 2: Impact of dry, rain and storm weather influent dynamics on *TSS* and *DO* in the membrane tanks, *DO* in the second aerobic zone and *TSS* in the first anoxic zone. The 2nd and 3rd day of the 7 day evaluation period are shown



Qi
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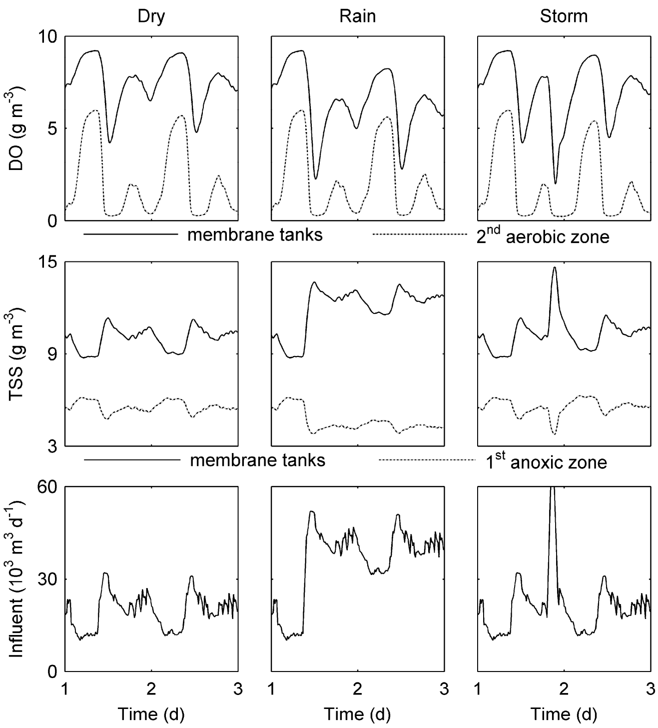

Dry
Rain
Storm
DO (g m-3)
10
5
0
membrane tanks
2nd aerobic zone
TSS (g m-3)
15
9
3
membrane tanks
1st anoxic zone
Influent (103 m3 d-1)
60
30
0
1
2
3
Time (d)

BSM-MBR: A Benchmark Simulation Model to Compare Control and Operational Strategies for Membrane Bioreactors

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2011-03-01T00:00:00Z

Thomas Maere, Bart Verrecht, Stefanie Moerenhout, Simon Judd, Ingmar Nopens. BSM-MBR: A Benchmark Simulation Model to Compare Control and Operational Strategies for Membrane Bioreactors. Water Research, Volume 45, Issue 6, March 2011, Pages 2181–2190.

http://dx.doi.org/10.1016/j.watres.2011.01.006