Plant-wide (BSM2) evaluation of reject water treatment with a SHARON-Anammox process

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Abstract In wastewater treatment plants (WWTPs) equipped with sludge digestion and dewatering systems, the reject water originating from these facilities contributes significantly to the nitrogen load of the activated sludge tanks, to which it is typically recycled. In this paper, the impact of reject water streams on the performance of a WWTP is assessed in a simulation study, using the Benchmark Simulation Model no. 2 (BSM2), that includes the processes describing sludge treatment and in this way allows for plant-wide evaluation. Comparison of performance of a WWTP without reject water with a WWTP where reject water is recycled to the primary clarifier, i.e. the BSM2 plant, shows that the ammonium load of the influent to the primary clarifier is 28% higher in the case of reject water recycling. This results in violation of the effluent total nitrogen limit. In order to relieve the main wastewater treatment plant, reject water treatment with a combined SHARON-Anammox process seems a promising option. The simulation results indicate that significant improvements of the effluent quality of the main wastewater treatment plant can be realized. An economic evaluation of the different scenarios is performed using an Operating Cost Index (OCI).

Keywords Anammox; benchmarking; BSM2; nitrogen removal; plant-wide modelling; reject water treatment; SHARON; simulation; wastewater treatment

Introduction

The influent nitrogen (N) load of wastewater treatment plants (WWTPs) is increased considerably when reject water, originating from sludge digestion and dewatering systems, is recycled to it. The reject water stream, representing typically only 2% of the volume of the influent wastewater stream, can contribute up to 25% of the N load of the influent to the activated sludge process. This is especially problematic in case the latter has a limited aeration/nitrification/denitrification capacity. In order to relieve the main plant, it can be decided to treat the reject water stream before recirculation, e.g. through the SHARON-Anammox process (van Dongen *et al.*, 2001). In this process, half of the ammonium in the reject water is nitrified to nitrite in the SHARON reactor. Nitrate formation is suppressed by working at high temperatures combined with maintaining an appropriate sludge retention time, that is equal to the hydraulic retention time as a SHARON reactor is typically operating without sludge retention. In the subsequent Anammox reactor, almost equimolar

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amounts of ammonium and nitrite are combined to form di-nitrogen gas in the anaerobic ammonium oxidation (Anammox) reaction. With the combined SHARON-Anammox process, which is fully autotrophic, substantial savings on aeration costs (up to 63%) and external carbon addition costs (up to 100%) are realized in comparison with conventional nitrification-denitrification over nitrate, minimizing CO_2 and sludge production.

In this paper, model simulations are used as a tool for evaluating the impact of the recirculation of a reject water stream and to examine the effect of reject water treatment with SHARON-Anammox on the activated sludge process. For this purpose, a preliminary version of the COST/IWA Benchmark Simulation Model no. 2 (BSM2, Jeppsson *et al.*, 2006) is used. This model includes pre-treatment of wastewater as well as the processes describing sludge treatment and is in this way suitable for plant-wide evaluation. In order to also include the effect of reject water treatment, models of the SHARON and Anammox processes were implemented in the existing BSM2 model. A scenario without sludge treatment and therefore without reject water is compared with one in which untreated reject water is recycled to the main plant and one in which the reject water is treated with a combined SHARON-Anammox process before recirculation. An economic evaluation is performed on the basis of an Operating Cost Index (OCI).

The BSM2, SHARON and Anammox models

The layout of the BSM2, representing a 80,000 PE WWTP (Jeppsson *et al.*, 2006), is given in Figure 1. The predenitrifying activated sludge system (two anoxic reactors followed by three aerobic reactors) and the secondary clarifier are identical to the ones in the Benchmark Simulation Model no. 1 (BSM1, Copp, 2002). The BSM2 plant further contains a primary clarifier, a sludge thickener, an anaerobic digester and a dewatering unit. Plant performance evaluation is based on a one-year simulation, using influent data from Gernaey *et al.* (2005).

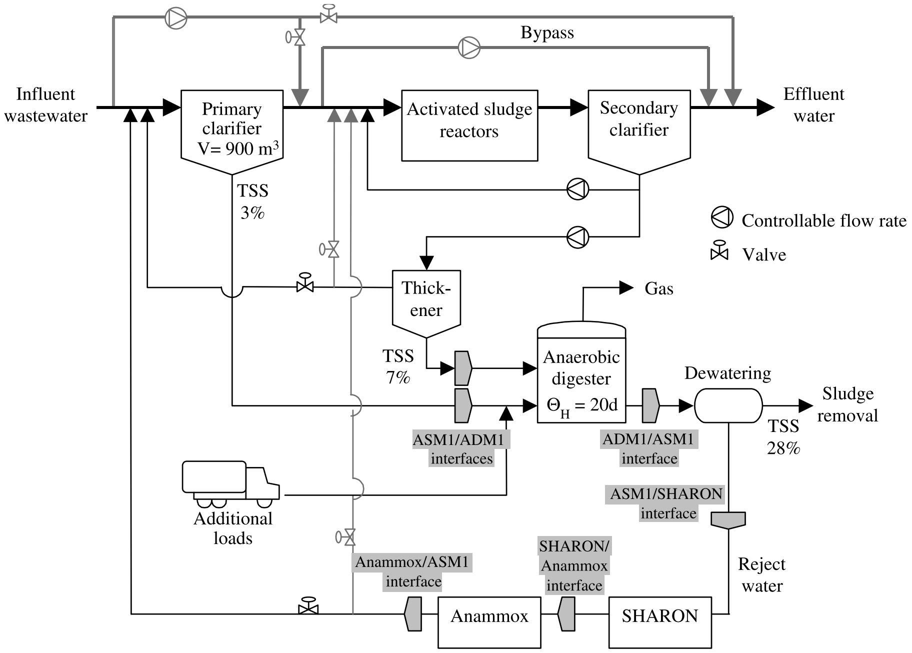

Figure 1 Extended BSM2 plant with anaerobic sludge digestion and reject water recirculation, adapted from Jeppsson *et al.* (2006). The location for inclusion of the SHARON and Anammox processes is indicated, as well as the necessary additional model interfaces

For the simulation study described here, the BSM2 plant is operated with the default closed-loop strategy, as proposed by Vrecko *et al.* (2006), with the following adjustments: the maximum internal recycle flow rate is limited to three times the average influent flow rate during dry weather in BSM1 instead of allowing up to five times this value; the external carbon flow rate is adjusted to maintain a constant nitrate set point of $10\,\mathrm{gN\,m^{-3}}$ in the last reactor, instead of applying an external carbon flow rate proportional to the influent flow rate as in the default BSM2 closed loop control strategy.

The SHARON reactor model was developed by Volcke *et al.* (2002) on the basis of the model of Hellinga *et al.* (1999). It consists of both liquid and gas phase mass balances and takes into account the effect of varying air flow rate on the transport coefficients for O_2, CO_2 and N_2 between the two phases. The model further considers pH effects that occur during nitrification of highly concentrated streams. More details can be found in Volcke (2006). The SHARON reactor volume was set constant at $338\,\mathrm{m^3}$, a value that corresponds to a hydraulic retention time of ~ 1.25 days for the 95-percentile value of the reject water flow rate, i.e. the value that is only exceeded 5% of the time. The SHARON reactor is cyclically operated with aerobic/anoxic periods in such a way that an aerobic sludge retention time of 1.25 days is maintained, despite the varying influent flow rate. No significant denitrification takes place, as the reject water stream contains almost no carbon source. During the aerobic periods, the oxygen concentration is controlled to a set point of $1.5\,\mathrm{g\,m^{-3}}$ by adjusting the air flow rate. The Anammox reactor model describes a CSTR of $75\,\mathrm{m^3}$ with almost complete (99.5%) biomass retention. Anammox kinetics are based on the model proposed by Dapena-Mora *et al.* (2004). Inhibition of Anammox growth by nitrite is incorporated using Haldane kinetics, with an inhibition coefficient of $15\,\mathrm{gN/m^3}$. A constant temperature of 35 °C has been assumed for both reactors.

As the different submodels are based on different state variables, special attention was devoted to the model interfaces, in the way described by Volcke *et al.* (2006). All models were implemented in Matlab-Simulink.

Economic evaluation procedure

Optimal design and operation of a process is a trade-off between effluent quality and the associated investment and operating costs. An Operating Cost Index (OCI) is a useful tool for simplifying the cost analysis necessary to make the trade-off. It includes the most important operating cost factors and indicates potential cost savings that can be made by introducing control strategies or plant design changes. Information on investment costs for the necessary equipment will then only be gathered for those control strategies that promise substantial operating cost savings. Vanrolleghem and Gillot (2002) previously demonstrated the use of an OCI to compare control strategies using the BSM1 (Copp, 2002).

In this study, the OCI (in €/year) is defined as follows:

$$OCI = \gamma_1 EQ + \gamma_2 (AE_{BSM2} + AE_{SH} + ME_{BSM2} + ME_{SH} + PE_{BSM2} + PE_{SH,An}) + HE^{net} + \gamma_3 SP_{BSM2} + \gamma_3 (SP_{SH} + SP_{An}) + \gamma_4 EC - \gamma_5 MP$$

with the following terms, defined by Copp (2002) and by Vrecko and Gernaey (2005). The effluent quality term (EQ) accounts for suspended solids (TSS), chemical oxygen demand (COD), biochemical oxygen demand (BOD), Kjeldahl-N (TKN) and nitrate (NO) in the effluent of the main WWTP. Aeration energy is calculated for both the main plant (AE_{BSM2}) and the SHARON reactor (AE_{SH}). The term ME_{BSM2} combines mixing energy in the activated sludge tanks and the anaerobic digester, while ME_{SH} denotes the mixing energy consumed in the SHARON reactor during non-aerated periods. No mixing device is installed in the Anammox reactor, as mixing is established by the produced di-nitrogen gas. Pumping energy is calculated for the internal and external recycle flow, the waste sludge flow, the primary settler underflow, the thickener and dewatering underflow (all included in the PE_{BSM2} term) and for the flow from the SHARON to the Anammox reactor ($PE_{SH,An}$). Gravitational flow (no pumping energy required) is assumed for the remaining flows. The net heating energy ($HE^{net} > 0$) represents the energy needed to heat the flow of sludge fed to the anaerobic digester in case the heat generation during electricity production from biogas is insufficient. The sludge production SP_{BSM2} is calculated from accumulated (in activated sludge unit, settler, primary clarifier, anaerobic digester) and disposed (dewatering underflow) solids of the plant. The term SP_{An} accounts for solids accumulated in the Anammox reactor in case the reject water is treated with a SHARON-Anammox process. However, the amount of sludge accumulated in the SHARON reactor is neglected, as this reactor is operated without biomass retention. The cost for external carbon addition is represented by the term *EC*. The term *MP* denotes cost savings as produced methane in the anaerobic digester.

The weights for the pollution units ($\gamma_1 = 50$), energy ($\gamma_2 = 25$) and sludge disposal ($\gamma_3 = 75$) are taken from Vanrolleghem and Gillot (2002). The weights for external carbon addition ($\gamma_4 = 75$) and methane production ($\gamma_5 = 150$) were set in such a way that their relative value compared to γ_1, γ_2 and γ_3 is the same as in the OCI proposed for BSM2 (Vrecko *et al.*, 2006).

The OCI includes the operating costs that differ between the scenarios under study. Savings in operating costs between two operating modes thus equal the investment costs that can be supported for establishing a SHARON/Anammox reactor and for the purchase and installation of extra equipment to establish a control strategy.

Simulation results

Plant-wide performance was assessed for three different scenarios:

1. the ‘standard’ BSM2 layout, with recirculation of reject water to the primary clarifier;
2. the BSM2 layout without sludge treatment and thus without reject water;
3. a WWTP in which the reject water is treated with a SHARON-Anammox process before recycling to the main WWTP.

Figure 2 compares the ammonium load of the influent to the primary clarifier (including the reject water) with the one of the reject water stream. The reject water stream

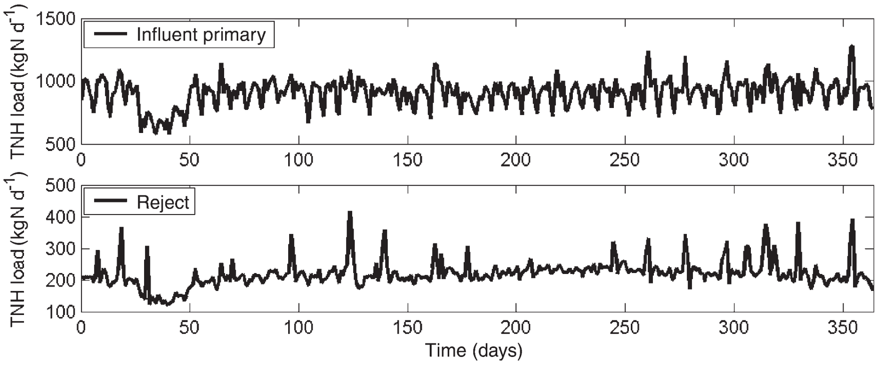

Figure 2 Ammonium load of influent stream to primary clarifier versus ammonium load of reject water (daily mean values) in case of recycling of untreated reject water

(mean flow rate 172 m^3 day^{-1}) only represents 0.8% of the total flow (mean 21,138 m^3 day^{-1}) to the primary clarifier, but it contains such high ammonium concentrations (mean 1,372 gN m^{-3}) that the ammonium load of the reject water stream represents a significant part (mean: 21%) of the ammonium load to the primary clarifier (mean: 1,122 kgN day^{-1}).

When comparing these results with the scenario without reject water (results not shown), it is clear that the ammonium load of the influent increases by 28% when reject water is recycled. In case of reject water treatment with a SHARON-Anammox process, the total ammonium load to the primary clarifier is reduced by 25% (mean 901 kgN day^{-1}, results not shown) for the operating mode suggested in this paper. Note that this value may be further improved by optimizing the operation of the SHARON-Anammox process.

The effluent quality of the WWTP is compared for the three scenarios under study. Table 1 gives the 95% percentiles of the effluent concentrations, i.e. the effluent concentrations that are exceeded 5% of the time, as well as the percentage of time the effluent limits are violated. In Figure 3, daily mean values of the effluent concentrations are plotted. As the effluent concentrations of COD, BOD and TSS do not differ much between the three treatment options and the corresponding effluent limits are met nearly the whole time, only the results for total N and ammonium are shown. The increased ammonium load due to recirculation of untreated reject water causes frequent violations of the effluent total N limit: 21% of the time, compared with 0% for the case without reject water. When treating the reject water with a SHARON-Anammox process before recirculation, the effluent quality improves significantly, exceeding the total N effluent limit only 1% of the time. For all three scenarios, the effluent ammonium limit is exceeded a significant part of the time. However, the percentage of time the limit is violated is reduced from 31% to 19% by treatment of the reject water with SHARON-Anammox before recirculation, which is comparable to the case without reject water (17% of the time). The latter situation serves as a reference case for what can be obtained by ideal reject water treatment. Low temperature during the winter period ($t = 100$ to $t = 250$ days) is one of the main reasons for the poor performance of the nitrification process. It is clear that this should be remedied by optimizing the control of the main WWTP rather than the reject water treatment, for example by allowing aeration in one of the denitrification tanks when temperatures are low.

The OCI defined above was used to compare the three scenarios on an economic basis. Regarding the effluent quality, Table 2 shows that main differences are established in terms of TKN and NO in case the reject water is treated before recirculation, and the concentration of N compounds in the effluent is significantly reduced, to values that approach the ones in case the reject water is not recycled. In case of recirculation of reject water, the WWTP effluent contains considerably more COD. This is explained

Table 1 Effluent quality in terms of total N and ammonium

	BSM2	No reject water	Reject treatment with SHARON-Anammox
Total N limit: 18 gN m^{-3}			
95% percentile (gN/m^3)	21	15	16
% of time limit violation	21	0	1
Ammonium limit: 4 gN m^{-3}			
95% percentile (gN/m^3)	10	7	7
% of time limit violation	31	17	19

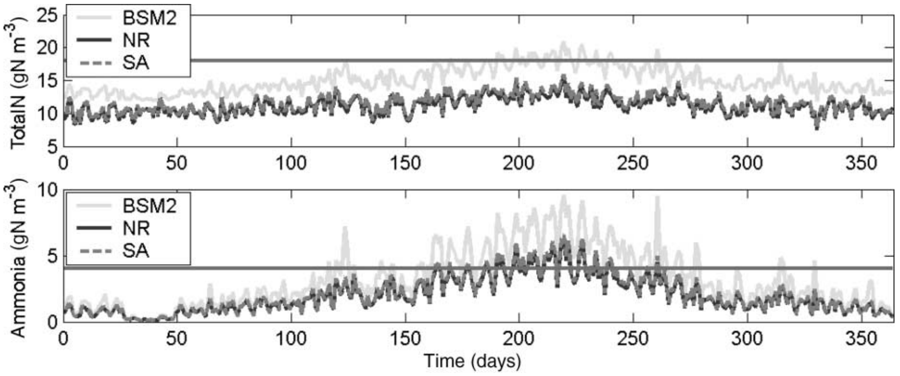

Figure 3 Effluent quality in terms of total N and ammonium; NR: scenario without reject water; SA: scenario with treatment of reject water with SHARON-Anammox

almost completely by an increased amount of soluble inert material (S_I), which is not biodegradable.

The aeration energy needed in the activated sludge tanks is decreased in case of treatment of reject water compared to the scenario with recirculation of untreated reject water. When also considering the aeration energy consumed in the SHARON reactor, the total aeration energy is comparable, but it is important to note here that an higher overall amount of ammonium has been oxidized. Indeed, ammonium removal from the reject water stream with the SHARON-Anammox processes consumes relatively less oxygen than in the activated sludge reactors as typically half of the ammonium is oxidized to nitrite only in the SHARON process and the other half is converted without oxygen usage in the Anammox process.

Table 2 Economic evaluation (units: *EQ* [kgPU day^{-1}]; *AE/ME/PE/HE^{net}* [kWh day^{-1}]; *SP* [kgCOD day^{-1}]; *EC* [kgCOD day^{-1}]; *MP* [kgCH$_4$ day^{-1}])

Cost factors	BSM2	No reject water	SHARON-Anammox
Effluent quality (*EQ*)			
TSS	711	683	707
COD	1,595	1,025	1,592
BOD	143	133	137
TKN	2,339	1,775	1,871
NO	3,960	2,727	2,887
Total	8,748	6,342	7,194
Aeration energy (*AE*)	7,773	7,198	7,243 (538; 0)*
Mixing energy (*ME*)	648	240	648 (15; 0)*
Pumping energy (*PE*)	2,311	2,699	2,658 (7; 0)*
Net heating energy (*HE^{net}*)	0	0	0
Sludge production (*SP*)	3,187	5,979	3,067 (0.005; 13)*
External carbon addition (*EC*)	585	20	27
Methane production (*MP*)	858	0	820
Associated costs [€/year]			
Effluent quality (*EQ*)	437,419	317,105	359,683
Aeration energy (*AE*)	194,333	179,949	194,526
Mixing energy (*ME*)	16,200	6,000	16,571
Pumping energy (*PE*)	57,764	67,474	66,623
Sludge production (*SP*)	239,002	448,422	230,975
External carbon addition (*EC*)	43,889	1,491	2,016
Methane production (*MP*)	− 128,766	0	− 122,973
Total (= OCI)	859,842	1,020,442	747,422

*Values between brackets refer to additional contributions from SHARON, respectively Anammox

As the Anammox process converts ammonium and nitrite to di-nitrogen gas in an autotrophic way, external carbon source addition has been made almost redundant in case of reject water treatment, still realizing a much better effluent quality in terms of nitrate.

Sludge disposal costs (SP) are very high for the scenario without on-site sludge treatment (no reject water). For the scenario with recirculation of reject water, treated with SHARON-Anammox, less sludge is produced than in the case when the reject water is not treated. This is due to the ammonium oxidation to nitrite only in the SHARON reactor and due to the very low yield of the Anammox biomass. The smaller sludge production in case of reject treatment before recirculation is the reason why a little less methane is produced in comparison to recirculation of non-treated reject water. Note that the heat generated during methane production is more than sufficient for heating the anaerobic digester ($HE^{net} = 0$).

Comparing the total cost indices for the three scenarios, the case with external sludge treatment (no reject water) clearly has the largest operating costs. Still, one might jump to the conclusion that the yearly extra costs of 160,600 € do not counterbalance investment costs for sludge treatment (digester, thickener and dewatering equipment) and for this reason it may seem economically more feasible to treat the sludge externally. However, it is important to note that the sludge treatment costs are calculated on TSS basis, but do not consider the TSS concentration of the sludge. Sludge transportation costs are not included. For the relatively large WWTP (80,000 PE) represented by BSM2, it seems unrealistic to transport the large sludge volumes with very low solids concentration from the primary and secondary clarifier for external treatment. Therefore, this scenario should be considered as a reference case for ideal reject water treatment rather than as a realistic treatment option.

Comparing the scenario with recirculation of untreated reject water with the one in which the reject water is treated by SHARON-Anammox before recycling, it is not clear whether the yearly operating costs savings of 112,420 €/year will warrant the investment costs for installing a SHARON and Anammox reactor. The aeration capacity of the activated sludge tanks of the BSM2 plant has been shown to be sufficient to oxidize at least part of the ammonium load originating from the reject water stream. For this reason, not as much is gained by implementing a SHARON-Anammox process as when there would be no spare aeration capacity of the activated sludge tanks. However, one must keep in mind that a considerable effluent quality improvement is realized by treatment of the reject stream before recirculation and that the permit of the WWTP may be in danger when effluent standards are not met.

Conclusions

The effect of reject water originating from sludge treatment on the performance of the activated sludge process, to which this stream is typically recycled, was examined in a plant-wide simulation study using the Benchmark Simulation Model no. 2, developed by the IWA Task Group on Benchmarking. A scenario without sludge treatment and therefore without reject water was compared with one in which untreated reject water is recycled to the main plant and one in which the reject water is treated with a combined SHARON-Anammox process before recirculation. Recirculation of the untreated reject water stream, representing 21% of the total influent ammonium load, unacceptably worsens the total N concentration in the effluent of the BSM2 plant. The effluent quality was improved significantly by treatment of the reject water stream with a SHARON-Anammox process before recirculation. Moreover, in the case of reject water treatment, external carbon source addition was made almost redundant and less sludge was produced, while more ammonium was converted for about the same aeration energy consumption. Although the yearly operating cost savings resulting from reject water treatment with a SHARON-Anammox process as such only partly warrant the associated investment costs, it is a promising option to meet the required effluent limits and prevent the WWTP from losing its permit.

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