Minimising Overall Greenhouse Gas Emissions from Wastewater Treatment Plants by Implementing Automatic Control

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Abstract: In this paper, an extension to the IWA Benchmark Simulation Model No 2 (BSM2) is presented to estimate greenhouse gas (GHG) emissions from wastewater treatment plants. Thus, the traditional effluent quality (EQI) and operational cost indices (OCI) used to evaluate the performance of control systems of wastewater treatment plants (WWTP) are complemented with a new dimension dealing with GHG emissions. This GHG evaluation is based on a comprehensive dynamic model that estimates all potential on-site and off-site sources of GHG emissions. The case study investigates the overall performance of one control strategy and demonstrates the substantial reductions in effluent pollution, operating costs and GHG emissions that can be achieved when automatic control is implemented. Furthermore, the study is complemented with a scenario analysis that examines the role of i) the dissolved oxygen (DO) set-point, ii) the sludge retention time (SRT) and iii) the organic carbon/nitrogen ratio (COD/N) as promoters of GHG emissions. The results of this study confirm the synergies and trade-offs amongst the formation of CO₂, CH₄ and N₂O when different operational strategies are implemented, their correlation with the effluent quality (EQI) and operating cost (OCI) indices and the need to reach a compromise solution in order to achieve optimal performance.

Keywords: Activated Sludge Modeling, Benchmarking, Global warming, Model Based Evaluation, Multi-criteria Decision Making, Process control, Sustainability

INTRODUCTION

The increasing demands on effluent quality at lower operational costs have promoted the development of new technologies and the implementation of control concepts to improve the overall performance of wastewater treatment plants (WWTP). Full-scale applications have shown the feasibility of automatic control in aeration systems, chemical dosage and recycle flows (Oennerth et al., 1996; Ingildsen et al., 2002; Devisscher et al., 2002; Olsson et al., 2005). Dynamic simulation studies have also been used to compare the performance of different control strategies (Zhao et al., 1995; Stare et al., 2007; Flores-Alsina et al., 2009) or to evaluate them before full-scale implementation (Ayesa et al., 2006). Plant-wide operation has also been introduced to take into account the interactions between the processes (Gujer and Erni 1978, Lessard and Beck, 1993; Jeppsson et al., 2007). Nevertheless, the increasing interest for greenhouse gas (GHG) emissions from wastewater treatment leads to re-think the traditional engineering approaches by adding this new dimension. Therefore, new tools are needed to estimate the GHG emissions and evaluate different operation schemes that prevent or minimize their generation in WWTP.

So far, different models can be found in literature trying to describe the GHG-related mechanisms involved in wastewater treatment. These models can be subdivided in three main groups. The first group corresponds to empirical models (e.g. IPCC, 2006; LGO, 2008; NGER, 2008) that are used to make inventories and that provide an order of magnitude of the production of greenhouse gases. However, these models are at an early stage of their development and have high uncertainty and variability (Pagilla et al., 2009). The second group includes simple comprehensive process models for wastewater and biosolids treatment (Cakir and Stenstron, 2005; Monteith et al., 2005; Bridle et al., 2008; Foley et al., 2009). Finally, the third group of models consists of mechanistic models
that dynamically describe the production of certain greenhouse gases. The Anaerobic Digestion Model 1 (ADM1) proposed by Batstone et al. (2002) describes CH₄ and CO₂ emissions under anaerobic conditions. Regarding anoxic-aerobic processes there have been attempts to describe nitrification and denitrification to include the intermediates NO₂, NO and N₂O (von Schulthess and Gujer, 1996; Hiatt and Grady, 2008a).

Changes in the influent load, the temperature and the operating conditions influence the production of GHGs (Kampschreur et al., 2008; Hiatt and Grady, 2008b; Bani Shahabadi et al., 2009) and the use of control can be useful to account for these dynamics and maintain GHGs at acceptable levels. The main objective of this paper is to demonstrate that GHGs emissions can be minimized when automatic control is implemented. A plant-wide dynamic model is used evaluate different options of control in terms of effluent quality, operating costs and GHG emissions.

2. METHODS

2.1. Wastewater treatment plant under study and process models

The WWTP under study is the IWA BSM2 described in Jeppsson et al., (2007) and redefined in Nopens et al. (in press). The activated sludge unit is a modified Ludzack-Ettinger configuration consisting of 5 tanks in series. Tanks 1 (ANOX1) and 2 (ANOX2) are anoxic, while tanks 3 (AER1), 4 (AER2) and 5 (AER3) are aerobic. AER3 and ANOX1 are linked by means of an internal recycle. The BSM2 plant further contains a primary (PRIM) and a secondary (SEC) clarifier, a sludge thickener (THK), an anaerobic digester (AD), a storage tank (ST) and a dewatering unit (DW). The yearly average influent flow of the plant is 20648 m³·d⁻¹ and the organic and nitrogen loads are 12240 kg COD·d⁻¹ and 1150 kg N·d⁻¹ respectively.

The process models used in this study are the models described in the standard BSM2 but with the biokinetic model ASM1 replaced by the ASMN model (Hiatt and Grady, 2008a) with few modifications to account for the necessities of this work. This model incorporates two nitrifying populations – ammonia oxidizing bacteria (AOB) and nitrite oxidizing bacteria (NOB) – using free ammonia and free nitrous acid, respectively as their substrates. The model also incorporates four step denitrification (sequential reduction of nitrate to nitrogen gas via nitrite, nitric oxide, and nitrous oxide), using individual reaction specific parameters. The processes of nitrite reduction to ammonia and the mixotrophic growth of the nitrite oxidizing bacteria are not included. The state variables salt, biodegradable AOB inhibitor and priority pollutant are neither considered. The parameter values suggested in Hiatt and Grady (2008a) were used, except for the KₚNA that was reduced from 1·10⁻⁴ (used for high nitrogen loads) to 1·10⁻⁶ g·m⁻³ (used for low nitrogen loads) to promote NOB growth. In order to account for seasonal variability, liquid-gas saturation constants, kinetic parameters, transfer coefficients and equilibrium reactions are temperature dependent. Stripping equations for the gases were implemented as in Foley et al. (2009). The interfaces presented in Nopens et al. (2009) have been modified to link ASMN and ADM1, by considering COD and N balances for all oxidized nitrogen compounds.

The simulations have been performed in WEST(R), running a steady state simulation (200 days) followed by a dynamic simulation of 609 days. Only the data generated during the last 364 days of the dynamic simulation are used for plant performance evaluation.

2.2. Effluent quality (EQI) and operational cost (OCI) indices

The effluent quality and the operational cost are used to evaluate the proposed control strategies in the modified version of the BSM2. Compared to the proposal of Nopens et al. (in press) the oxidized nitrogen species (NO₃⁻, NO₂⁻, NO and N₂O) in the effluent are lumped into NOₓ on a nitrogen basis. The weight used for NO₃⁻ (10) is also used for NOₓ. In addition, the economic objectives are evaluated using the operating cost index (OCI), which includes a broad range of operating costs related to a WWTP (Nopens et al., in press).
2.3. Estimation of greenhouse gas emissions

The comprehensive approach suggested by Monteith et al. (2005) and extended in Briddle et al. (2008) is used to estimate all potential GHG emissions from the studied WWTP that cannot be obtained from the explicit results of the modified BSM2. The overall model comprises the estimation of the following GHG emissions: i) bio-treatment, ii) sludge processing, iii) net power, iv) embedded GHG emissions from chemical use and finally v) sludge disposal and reuse.

- **Bio-treatment.** The emission from the activated sludge section includes the CO₂ generated from biomass respiration and BOD oxidation, the N₂O generated from nitrogen removal and the CO₂ credit from nitrification. The first two processes are estimated following the methodology proposed by Monteith et al. (2005). N₂O emissions are given by the modified ASMN model. Finally, the credit from nitrification is calculated with the factor 4.49 kg of CO₂ consumed · (kg N nitrified)⁻¹.

- **Sludge processing.** The emissions of GHG during sludge treatment are mainly generated in the anaerobic digester. Direct biogas CO₂ and CH₄ emissions are quantified using the ADM1. In this case it is assumed that the biogas is fed directly into a gas-fired combustion turbine converting the CH₄ into CO₂ and generating electricity and heat (in turn used to heat the anaerobic digester). The CO₂ generated during anaerobic digestion and the CO₂ produced in the combustion are released to the atmosphere.

- **Net power GHG.** The total energy consumption is quantified using the operational cost index defined in Nopens et al. (in press). This index includes the different energy consumptions in the plant such as aeration, pumping, mixing and heating (in kW·h·d⁻¹). The credit refers to the electricity generated by the turbine and it is calculated by using a factor for the energy content of the methane gas (50014 MJ · (kg CH₄)⁻¹) and assuming a 43% efficiency for electricity generation. The net power is the difference between the total energy consumption and the credit.

- **Chemicals.** The embedded GHG emissions associated with chemicals used at the WWTP have been limited to the external carbon source. These emissions are estimated by using the emission factor of 1.54 g CO₂e · g methanol⁻¹ (Dong and Steinberg, 1997).

- **Sludge disposal and reuse.** CO₂ emissions associated with trucking of bio-solids are quantified by multiplying the truck movements by the distance to the reuse. The CO₂ emissions by mineralization are calculated based on the sludge mass times the carbon concentration times the factor of CO₂ to carbon. It is assumed that 38% of sludge goes to agriculture, 45% to a compost site and 17% to forestry (Briddle et al., 2008).

It is important to highlight that to deal with the different nature of the generated GHG (CO₂, CH₄ and N₂O), they are converted in units of CO₂ equivalent (CO₂e).

2.4. Implemented control strategy

The BSM2 is simulated under open-loop and closed-loop control. The operational settings under open-loop have the following characteristics: \( Q_{\text{int}} = 61 \) 944 m³·d⁻¹ (internal recycle flow rate), \( Q_{\text{w}} = 400 \) m³·d⁻¹ (waste flow rate), \( Q_{\text{r}} = 20648 \) m³·d⁻¹ (external recirculation flow rate), \( Q_{\text{carb}} = 5 \) m³·d⁻¹ (external carbon source addition rate) and \( k_{L,a3}=k_{L,a4}=k_{L,a5} = 140 \) d⁻¹ (aeration intensity, represented as the volumetric oxygen transfer coefficient). The closed-loop configuration includes the two simple PI controllers. The first loop controls the dissolved oxygen (DO) in the second aerobic tank (AER2) at 2 g O₂·m⁻³ through manipulation of the aeration intensity (\( k_{L,a} \)), and the second loop controls the nitrate at 1 g N·m⁻³ in the second anoxic tank (ANOX2) by manipulating the internal recycle flow rate (\( Q_{\text{int}} \)). Sensor and actuator models are also included to obtain realistic signals.

3. RESULTS

Open and closed-loop simulations

The results obtained for the open (\( A_1 \)) and closed-loop (\( A_2 \)) simulations have been evaluated with respect to effluent quality, operating costs and GHGs production (see Table 1). With the implementation of the controllers (\( A_2 \)) the EQI is reduced by 5% (from 6461 kg poll·day⁻¹ to 6181
kg poll·day$^{-1}$) mainly due to improved denitrification. Thanks to the DO controller the quantity of oxygen returning from the aerobic to the anoxic reactor via internal recirculation was minimized. No differences are observed for COD, BOD$_5$ and TSS removal efficiencies. The implementation of the control strategy also allows a reduction of 6% in the operational cost. Table 2 shows that the main differences are attributed to the aeration system, which reduces the aeration energy due to a more efficient energy use adapting the airflow rate to the oxygen demand for both organic matter and nitrogen removal.

**Table 1.** Evaluation criteria for the different control strategies (yearly average)

<table>
<thead>
<tr>
<th>Evaluation criteria</th>
<th>Open-loop ($A_1$)</th>
<th>Closed-loop ($A_2$)</th>
<th>UNITS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Kjeldahl Nitrogen (TKN)</td>
<td>3.86</td>
<td>4.10</td>
<td>g N·m$^{-3}$</td>
</tr>
<tr>
<td>Total Nitrogen (TN)</td>
<td>15.04</td>
<td>13.22</td>
<td>g N·m$^{-3}$</td>
</tr>
<tr>
<td>Chemical oxygen demand (COD)</td>
<td>49.17</td>
<td>49.19</td>
<td>g COD·m$^{-3}$</td>
</tr>
<tr>
<td>Biochemical oxygen demand (BOD$_5$)</td>
<td>3.13</td>
<td>3.13</td>
<td>g COD·m$^{-3}$</td>
</tr>
<tr>
<td>Total suspended solids (TSS)</td>
<td>14.91</td>
<td>14.91</td>
<td>g TSS·m$^{-3}$</td>
</tr>
<tr>
<td>Effluent quality index (EQI)</td>
<td>6461</td>
<td>6181</td>
<td>kg poll·d$^{-1}$</td>
</tr>
<tr>
<td>Sludge production ($P_{sludge}$)</td>
<td>2699</td>
<td>2699</td>
<td>kg TSS·d$^{-1}$</td>
</tr>
<tr>
<td>Aeration energy (AE)</td>
<td>5626</td>
<td>4790</td>
<td>kWh·d$^{-1}$</td>
</tr>
<tr>
<td>Pumping energy (PE)</td>
<td>446</td>
<td>463</td>
<td>kWh·d$^{-1}$</td>
</tr>
<tr>
<td>Carbon addition (CS)</td>
<td>2000</td>
<td>2000</td>
<td>kg COD·d$^{-1}$</td>
</tr>
<tr>
<td>Mixing energy (ME)</td>
<td>768</td>
<td>768</td>
<td>kWh·d$^{-1}$</td>
</tr>
<tr>
<td>Heating energy (HE)</td>
<td>4285</td>
<td>4295</td>
<td>kWh·d$^{-1}$</td>
</tr>
<tr>
<td>Energy production from Methane (MP)</td>
<td>-15820</td>
<td>-15782</td>
<td>kWh·d$^{-1}$</td>
</tr>
<tr>
<td>OCI</td>
<td>14107</td>
<td>13254</td>
<td>-</td>
</tr>
<tr>
<td>Bio-treatment GHG emissions</td>
<td>0.451</td>
<td>0.376</td>
<td>kg CO$_2$·e·m$^{-3}$</td>
</tr>
<tr>
<td>Biomass respiration</td>
<td>0.179</td>
<td>0.178</td>
<td>kg CO$_2$·e·m$^{-3}$</td>
</tr>
<tr>
<td>BOD oxidation</td>
<td>0.212</td>
<td>0.212</td>
<td>kg CO$_2$·e·m$^{-3}$</td>
</tr>
<tr>
<td>Credit nitrification</td>
<td>-0.168</td>
<td>-0.167</td>
<td>kg CO$_2$·e·m$^{-3}$</td>
</tr>
<tr>
<td>N$_2$O emissions</td>
<td>0.228</td>
<td>0.152</td>
<td>kg CO$_2$·e·m$^{-3}$</td>
</tr>
<tr>
<td>Sludge processing GHG emissions</td>
<td>0.231</td>
<td>0.231</td>
<td>kg CO$_2$·e·m$^{-3}$</td>
</tr>
<tr>
<td>Net power GHG emissions</td>
<td>0.000</td>
<td>-0.038</td>
<td>kg CO$_2$·e·m$^{-3}$</td>
</tr>
<tr>
<td>Power</td>
<td>0.311</td>
<td>0.272</td>
<td>kg CO$_2$·e·m$^{-3}$</td>
</tr>
<tr>
<td>Credit power GHG emissions</td>
<td>-0.311</td>
<td>-0.310</td>
<td>kg CO$_2$·e·m$^{-3}$</td>
</tr>
<tr>
<td>Embedded GHG emissions from chemical use</td>
<td>0.099</td>
<td>0.099</td>
<td>kg CO$_2$·e·m$^{-3}$</td>
</tr>
<tr>
<td>Sludge disposal and reuse GHG emissions</td>
<td>0.193</td>
<td>0.193</td>
<td>kg CO$_2$·e·m$^{-3}$</td>
</tr>
</tbody>
</table>

The plant under control reduces the GHGs by 12% (from 0.975 to 0.860 kg CO$_2$·e·m$^{-3}$ treated wastewater). The main differences are found in the bio-treatment emissions and in the power consumption. A significant reduction of emitted N$_2$O (from 16 to 10 kg N$_2$O·day$^{-1}$) is observed since the use of the DO controller prevents the system from nitrite accumulation (see a detailed discussion in the following section). Moreover, there is a reduction in the off-site CO$_2$ emissions due to lower power consumption (as mentioned before for the cost index). The implemented basic controller does not suppose changes in both the addition of external carbon source and sludge line. For this reason the GHG emissions due to sludge processing, sludge disposal and reuse and the embedded emissions from chemical use remain at the same value. Finally, it has to be mentioned that the GHG estimations obtained in this study are within the range of values presented in Bridl et al. (2008) (0.9, 1.6 and 2.2 kg CO$_2$·e·m$^{-3}$) and in Pagilla et al. (2009) (from 0.34 to 1.25 kg·m$^{-3}$).

**Scenario Analysis**

A scenario analysis has been conducted to investigate which variables are worth looking for control in view of reducing GHG emissions. Therefore, we analyse how the results of the closed-loop control strategy ($A_2$) are affected by changing some of its settings. Scenario 1 evaluates the plant performance at the DO set-points of 1 and 3 gO$_2$·m$^{-3}$. Scenario 2 changes the sludge retention time by either increasing ($Q_W = 500$ m$^3$·d$^{-1}$) or decreasing ($Q_W = 300$ m$^3$·d$^{-1}$) the waste flow. Finally, in Scenario 3 the COD/N ratio is changed by modifying the dosage of external carbon source ($Q_{carb}$) at 0 and 10 m$^3$·d$^{-1}$. **Figure 1** presents the breakdown of GHG emissions for the different scenarios.
Effect of DO concentration (Scenario 1). Low DO concentrations (Figure 1, DO=1 g O₂·m⁻³) lead to a reduction of the CO₂ production due to lower energy consumption but increase the biotreatment emissions compared to A₂. There is an increase in the N₂O emissions due to accumulation of ammonia (Figure 2 left) and nitrite (Figure 2 right) mainly caused by the oxygen growth limitation of AOB and specially NOB. The resulting high NO₂⁻ concentrations in the anoxic reactor promote the production of N₂O. Figure 2 presents one year of data starting July 1st and with the summer holidays period (were load from industries is significantly reduced) between days 270 and 300. The yearly dynamics also show an increase in ammonia concentration in winter period with a consequent decrease of nitrite concentrations. During summer periods it is expected that more nitrite is accumulated. At a DO set-point of 3 g O₂·m⁻³ (Figure 1) there is an increase in the production of CO₂ due to higher energy consumption. In addition, there is more N₂O released due to incomplete denitrification caused by recirculation of DO from the aerobic to the anoxic reactor. No substantial changes are observed in GHG due to sludge treatment, sludge reuse and embedded use of chemicals.
**Effect of SRT (Scenario 2).** At lower SRT there is an increase of the GHG emissions due to sludge treatment and sludge disposal (Figure 1, Q_w = 500 m^3·day^{-1}) because the amount of TSS going to the sludge line increases (Figure 3 left) compared to A_2. As example, Figure 3 right shows how the quantity of CH_4 produced in the anaerobic digester increases at higher waste flows. Nevertheless, it is important to highlight that this comes with higher energy credit because more energy can be produced from the digester biogas. Thanks to these two factors lower sludge ages are supposed to reduce GHG emissions. At higher SRT (Figure 1, Q_w= 300 m^3·day^{-1}) the bio-treatment GHG emissions are higher mainly to an increase of the biomass respiration.

![Figure 3](image)

**Figure 3.** Dynamic evolution of the quantity of TSS going to the sludge line (left) and the CH_4 produced in the anaerobic digester (right) when the Q_w is changed

**Effect of COD/N ratio (Scenario 3).** A higher COD/N ratio (Q_{carb} = 10 m^3·d^{-1}) substantially decreases GHG emissions in the bio-treatment. The addition of carbon improves the overall denitrification process (see Figure 4 left) and therefore N_2O emissions decrease (Figure 4 right). However, the quantity of TSS going to the sludge line is higher and thus GHG emissions due to sludge processing and disposal are also increased. Also, the off-site CO_2 emission from chemical use increases, which makes this scenario the highest in terms of GHG emissions. At low COD/N ratio (Q_{carb} = 0 m^3·d^{-1}) the total emissions are extremely low (5718 kg CO_2·d^{-1}) because zero emissions are associated to chemicals and there is a significant decrease of bio-treatment emissions (The decrease in endogenous respiration is more important than the increase in N_2O emitted). Overall, in terms of GHG emissions it seems that is better not to add carbon.

![Figure 4](image)

**Figure 4.** Dynamic evolution of effluent NO_3^− (left) and the released N_2O (right) in ANOX when the Q_{carb} is changed

After analysing the synergies and trade-offs amongst the emission of GHG when different operational strategies are implemented it is necessary to study their correlation with the effluent quality (EQI) and operating cost (OCI) indices. Table 2 presents the results of total GHG emissions, EQI and OCI for the different evaluated scenarios.
It can be seen that the scenario with lowest GHG emissions ($Q_{\text{carb}}=0$) is the worst in terms of effluent quality. Contrary, the scenario with best effluent quality ($Q_{\text{carb}}=10$) generates high GHG emissions and is extremely expensive. A good compromise for the three indices is achieved for strategies A2 and $Q_w=500$, meaning that DO should be controlled around 2 mg O$_2$·L$^{-1}$, SRT should be kept at relatively low values and carbon addition should be optimized.

4. GENERAL DISCUSSION
The results obtained in this work show the potentials of extending the benchmark platform with calculation of GHG emissions as another dimension to evaluate control strategies. With the use of this platform it is now possible to see how the effluent standards, the economic consideration and the causes of GHG emissions are entangled. For this reason, the authors advocate for the use of multi-objective/multi-criteria evaluation techniques (Flores-Alsina et al., 2008) in order to include all these different factors during the decision process. Moreover, including this type of analysis during the evaluation of different treatment alternatives such as controller, operational strategies or design options will give to process engineers, decision makers or wastewater professionals a better idea of the sustainability of these options. Further research is needed to complete the study with other control strategies and to compare the results obtained with the other approaches available to estimate GHG emissions.

5. CONCLUSIONS
This paper has complemented the traditional effluent quality and cost criteria used for evaluation of control strategies with a new dimension dealing with GHG gases. The authors have applied an approach that evaluates and quantifies the different sources of GHG gases using dynamic modelling. The key findings of the paper are summarized in the following points:

- When controllers are implemented it is possible to reduce GHG emissions, improve effluent quality and reduce operating costs.
- Low DO set-points reduce the off-site CO$_2$ emissions but increase the N$_2$O production due to nitrite accumulation. High DO set-points increase both off-site CO$_2$ and N$_2$O emissions. In this study a good compromise is obtained with a DO set-point of 2 g O$_2$·m$^{-3}$.
- Low SRT reduces GHG emissions because the quantity of electricity produced from the anaerobic digester CH$_4$ is increased and endogenous respiration decreases.
- High external carbon source addition reduces effluent NO$_3^-$ but significantly increases the operational cost and the GHG emissions.

6. ACKNOWLEDGEMENTS
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7. REFERENCES


