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

Corominas Ll., Flores-Alsina X., Snip L. and Vanrolleghem P.A.

model*EAU*, Département de Génie Civil et Génie des Eaux. Pavillon Adrien-Pouliot, Université Laval, 1065, Avenue de la Médecine. Québec G1V 0A6, QC, Canada

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 CO_2, CH_4 and N_2O 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 CH_4 and CO_2 emissions under anaerobic conditions. Regarding anoxic-aerobic processes there have been attempts to describe nitrification and denitrification to include the intermediates NO_2, NO and N_2O (**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 $m^3 \cdot d^{-1}$ and the organic and nitrogen loads are 12240 kg $COD \cdot d^{-1}$ and 1150 kg $N \cdot d^{-1}$ 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 K_{FNA} that was reduced from $1 \cdot 10^{-4}$ (used for high nitrogen loads) to $1 \cdot 10^{-6}$ $g \cdot m^{-3}$ (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 (NO_3^-, NO_2^-, NO and N_2O) in the effluent are lumped into NO_x on a nitrogen basis. The weight used for NO_3^- (10) is also used for NO_x. 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 CO_2 generated from biomass respiration and BOD oxidation, the N_2O generated from nitrogen removal and the CO_2 credit from nitrification. The first two processes are estimated following the methodology proposed by **Monteith *et al.* (2005).** N_2O emissions are given by the modified ASMN model. Finally, the credit from nitrification is calculated with the factor 4.49 kg of CO_2consumed·(kg N nitrified)$^{-1}$.
-*Sludge processing*. The emissions of GHG during sludge treatment are mainly generated in the anaerobic digester. Direct biogas CO_2 and CH_4 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 CH_4 into CO_2 and generating electricity and heat (in turn used to heat the anaerobic digester). The CO_2 generated during anaerobic digestion and the CO_2 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 CH_4)$^{-1}$) 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 CO_2e·g methanol^{-1} (**Dong and Steinberg, 1997**).
-*Sludge disposal and reuse*. CO_2 emissions associated with trucking of bio-solids are quantified by multiplying the truck movements by the distance to the reuse. The CO_2 emissions by mineralization are calculated based on the sludge mass times the carbon concentration times the factor of CO_2 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 (CO_2, CH_4 and N_2O), they are converted in units of CO_2 equivalent (CO_2e).

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_{intr} = 61 944 m^3·d^{-1} (internal recycle flow rate), Q_W = 400 m^3·d^{-1} (waste flow rate), Q_r = 20648 m^3·d^{-1} (external recirculation flow rate), Q_{carb} = 5 m^3·d^{-1} (external carbon source addition rate) and k_La_3=k_La_4= k_La_5 = 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 O_2·m^{-3} through manipulation of the aeration intensity (k_La), 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_{intr}). 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)

Evaluation criteria	Open-loop (A_1)	Closed-loop (A_2)	UNITS
Total Kjeldahl Nitrogen (TKN)	3.86	4.10	g N·m^{-3}
Total Nitrogen (TN)	15.04	13.22	g N·m^{-3}
Chemical oxygen demand (COD)	49.17	49.19	g COD·m^{-3}
Biochemical oxygen demand (BOD_5)	3.13	3.13	g COD·m^{-3}
Total suspended solids (TSS)	14.91	14.91	g TSS·m^{-3}
Effluent quality index (EQI)	6461	6181	kg poll·d^{-1}
Sludge production (P_{sludge})	2699	2699	kg TSS·d^{-1}
Aeration energy (AE)	5626	4790	kWh·d^{-1}
Pumping energy (PE)	446	463	kWh·d^{-1}
Carbon addition (CS)	2000	2000	kg COD·d^{-1}
Mixing energy (ME)	768	768	kWh·d^{-1}
Heating energy (HE)	4285	4295	kWh·d^{-1}
Energy production from Methane (MP)	-15820	-15782	kWh·d^{-1}
OCI	14107	13254	-
Bio-treatment GHG emissions	0.451	0.376	kg CO_2e·m^{-3}
Biomass respiration	0.179	0.178	kg CO_2e·m^{-3}
BOD oxidation	0.212	0.212	kg CO_2e·m^{-3}
Credit nitrification	-0.168	-0.167	kg CO_2e·m^{-3}
N_2O emissions	0.228	0.152	kg CO_2e·m^{-3}
Sludge processing GHG emissions	0.231	0.231	kg CO_2e·m^{-3}
Net power GHG emissions	0.000	-0.038	kg CO_2e·m^{-3}
Power	0.311	0.272	kg CO_2e·m^{-3}
Credit power GHG emissions	-0.311	-0.310	kg CO_2e·m^{-3}
Embedded GHG emissions from chemical use	0.099	0.099	kg CO_2e·m^{-3}
Sludge disposal and reuse GHG emissions	0.193	0.193	kg CO_2e·m^{-3}

The plant under control reduces the GHGs by 12% (from 0.975 to 0.860 kg CO_2e·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_2O (from 16 to 10 kg N_2O·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_2e·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.

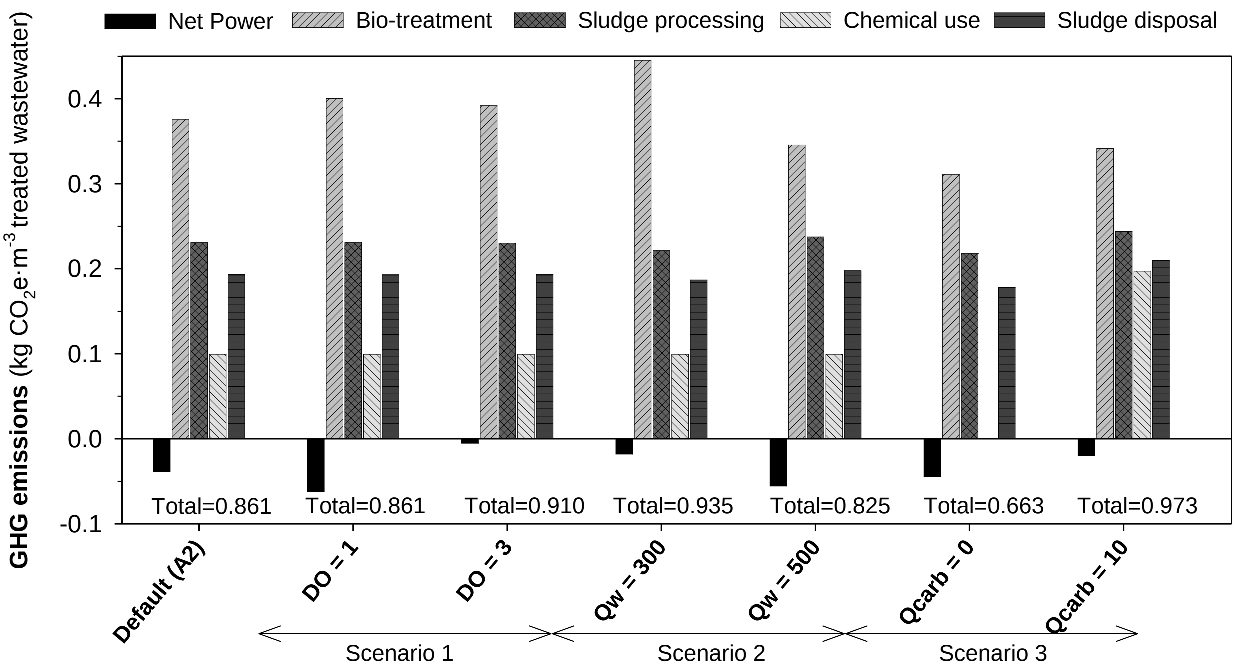

Figure 1. Breakdown of the GHG emissions for the different evaluated scenarios

Effect of DO concentration (Scenario 1). Low DO concentrations (**Figure 1**, DO=1 g $O_2 \cdot m^{-3}$) lead to a reduction of the CO_2 production due to lower energy consumption but increase the bio-treatment emissions compared to A_2. There is an increase in the N_2O 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 NO_2^- concentrations in the anoxic reactor promote the production of N_2O. **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 $O_2 \cdot m^{-3}$ (**Figure 1**) there is an increase in the production of CO_2 due to higher energy consumption. In addition, there is more N_2O 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.

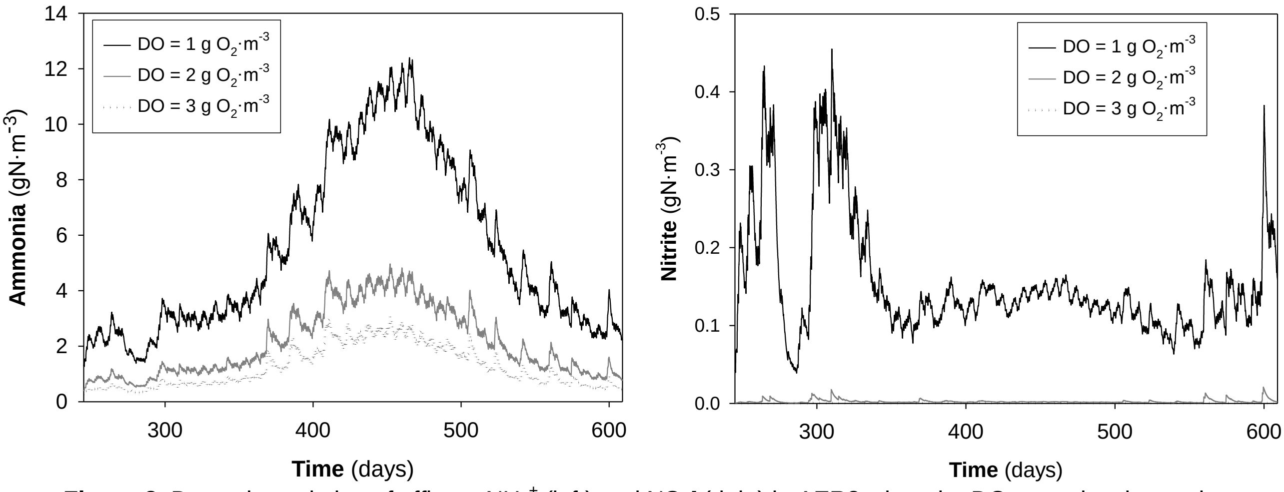

Figure 2. Dynamic evolution of effluent NH_4^+ (left) and NO_2^- (right) in AER3 when the DO set-point changed

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 $m^3 \cdot day^{-1}$) 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 $m^3 \cdot day^{-1}$) the bio-treatment GHG emissions are higher mainly to an increase of the biomass respiration.

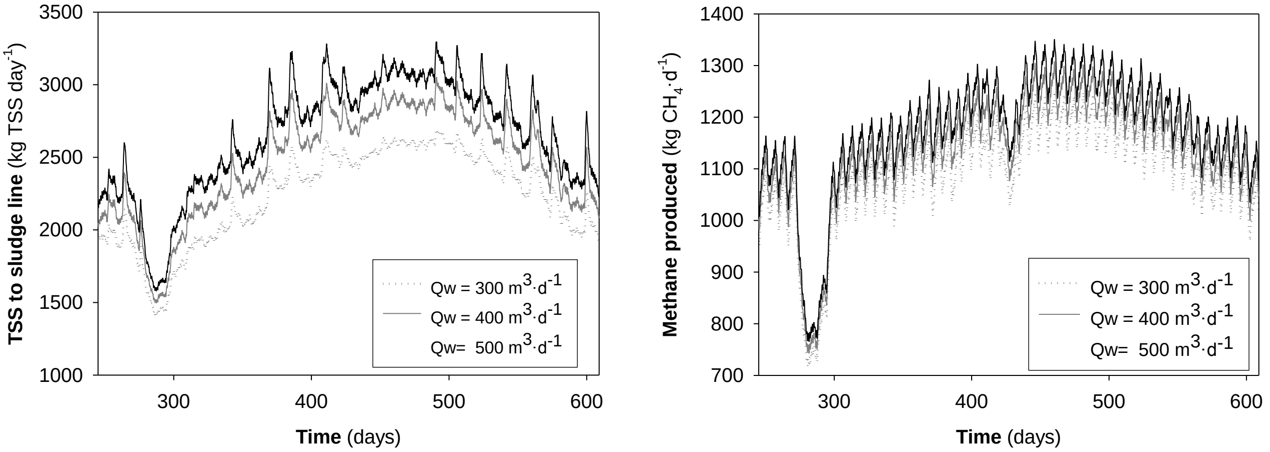

Figure 3. Dynamic evolution of the quantity of TSS going to the sludge line (left) and the CH4 produced in the anaerobic digester (right) when the Q_w is changed

Effect of COD/N ratio (Scenario 3). A higher COD/N ratio (Q_{carb} = 10 $m^3 \cdot d^{-1}$) 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 (Qcarb = 0 $m^3 \cdot d^{-1}$) the total emissions are extremely low (5718 kg $CO_2 \cdot d^{-1}$) 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.

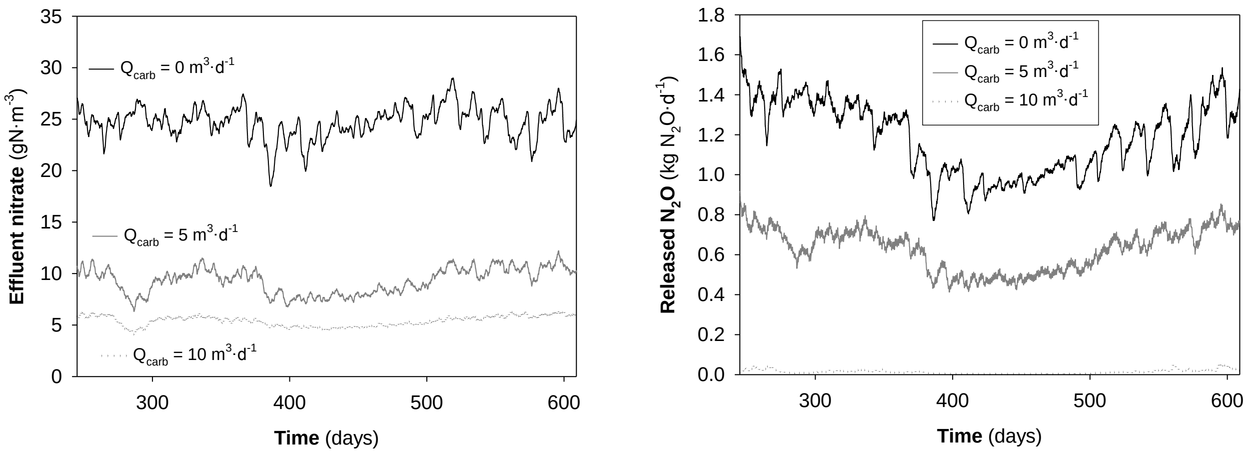

Figure 4. Dynamic evolution of effluent NO_3^- (left) and the released N_2O (right) in ANOX when the Q_{carb} is changed

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.

Table 2. Total GHG emissions, EQI and OCI for the different evaluated scenarios

	A2	DO=1	DO=3	Q_w=300	Q_w=500	Q_{carb}=0	Q_{carb}=10
Total GHG emissions (kg $CO_2e \cdot m^{-3}$)	0.861	0.861	0.910	0.935	0.825	0.663	0.973
EQI (kg poll$\cdot d^{-1}$)	6181	7517	5903	6613	6618	8411	5969
OCI (-)	13254	12318	13990	13440	13063	6485	20357

It can be seen that the scenario with lowest GHG emissions (Q_{carb}=0) is the worst in terms of effluent quality. Contrary, the scenario with best effluent quality (Q_{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 $O_2 \cdot L^{-1}$, 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_2O production due to nitrite accumulation. High DO set-points increase both off-site CO_2 and N_2O emissions. In this study a good compromise is obtained with a DO set-point of 2 g $O_2 \cdot m^{-3}$.
- 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

Peter Vanrolleghem holds the Canadian Research Chair on Water Quality Modeling.

7. REFERENCES

Ayesa E., De la Sota A., Grau P., Sagarna J.M, Salterain A. and Suescun J. (2006). Supervisory control strategies for the new WWTP of Galindo-Bilbao: the long run from the conceptual design to the full-scale experimental validation. *Water Sci. Technol.*, **53**(4-5), 193-201.

Bani Shahabadi M., Yerushalmi L. and Haghighat F. (2009). Impact of process design on greenhouse gas (GHG) generation by wastewater treatment plants. *Water Res.* **43**, 2679-2687.

Batstone D.J., Keller J., Angelidaki I., Kayuznyi S.V., Pavlostathis S.G., Rozzi A., Sanders W.T.M., Siegrist H. and Vavilin V.A. (2002). *Anaerobic Digestion Model No 1*. IWA STR No 13, IWA Publishing, London, UK.

Bridle T., Shaw A., Cooper S., Yap K.C., Third K. and Domurad M. (2008). Estimation of greenhouse gas emissions from wastewater treatment plants. *In:* Proceedings of IWA World Water Congress, Vienna, Austria. September 7-12, 2008.

Cakir F.Y. and Stenstron M.K. (2005). Greenhouse gas production: a comparison between aerobic and anaerobic treatment technology. *Water Res.* **39** (17), 4197-4203.
Devisscher M., Bogaert H,, Bixio D., Van de Velde J. and Thoeye C. (2002). Feasibility of automatic chemicals dosage control: a full-scale evaluation. *Water Sci. Technol.* **45** (4-5), 445-442.
Dong Y. and Steinberg M. (1997). Hynol – an economical process for methanol production from biomass and natural gas with reduced CO_2 emission. *Int. J. Hydrogen energ.* **22**(10-11), 971-977.
Flores-Alsina X., Comas J., Rodriguez-Roda I., Poch M., Gernaey K. and Jeppsson U. (2009). Evaluation of plant wide control strategies including the effects of filamentous bulking sludge. *Water Sci. Technol.* **60**(8), 2093-2103.
Flores-Alsina X., Sin G., Rodriguez-Roda I. and Gernaey K.V. (2008). Multicriteria Evaluation of Wastewater Treatment Plant Control Strategies under Uncertainty. *Wat. Res*. **42**, 4485-4497.
Foley J., de Haas D., Yuan Z. and Lant P. (2010). Nitrous oxide generation in full-scale biological nutrient removal wastewater treatment plants. *Water Res.* **44**,831-844.
Gujer W. and Erni P. (1978). The effect of diurnal ammonium load variation on the performance of nitrifying activated sludge processes. *Prog. Water Technol.* **10**(5/6), 391–407.
Hiatt W.C. and Grady C.P.L.Jr. (2008a). An updated process model for carbon oxidation, nitrification, and denitrification. *Water Environ. Res.* **80**, 2145-2156.
Hiatt W.C. and Grady C.P.L.Jr. (2008b). Application of the activated sludge model for nitrogen to elevated nitrogen conditions. *Water Environ. Res.* **80**, 2134-2144.
Ingildsen P., Jeppsson U., Olsson G. (2002). Dissolved oxygen controller based on on-line measurements of ammonium combining feed-forward and feedback. *Water Sci. Technol.* **45** (4-5), 453-460.
IPCC (2006). 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Intergovernmental Panel on Climate Change. Available at: http://www.ipccnggip.iges.or.jp/public/2006gl/index.html.
Jeppsson U., Pons M.N., Nopens I. Alex J., Copp J.B., Gernaey K.V., Rosen C., Steyer J.P. and Vanrolleghem. P.A. (2007). Benchmark Simulation Model No 2 – general protocol and exploratory case studies. *Water Sci. Technol.* **56** (8), 287-295.
Kampschreur M.J., van der Star W.R.L., Wielders H.A., Mulder J.W., Jetten M.S.M. and van Loosdrecht M.C.M. (2008). Dynamics of nitric oxide and nitrous oxide emission during full-scale reject water treatment. *Water Res.***42**, 812-826.
Lessard P. and Beck M.B. (1993). Modelling of the activated sludge process: a case of Norwich plant. *Water Res.* **27** (6), 963-978.
LGO (2008). Local Government Operations Protocol For the quantification and reporting of greenhouse gas emissions inventories. Version 1.0, September 2008. Available at: www.theclimateregistry.org/resources/protocols/local-government-operations-protocol/.
Monteith H.D., Sahely H.R., MacLean H.L. and Bagley, D.M. (2005). A rational procedure for estimation of greenhouse-gas emissions from municipal wastewater treatment plants. *Water Environ. Res.* **77**, 390-403.
NGER (2008). *National Greenhouse and Energy Reporting (Measurement) Technical Guidelines 2008 v1.1*. July 2008, Australian Government Department of Climate Change Available at: http://www.climatechange.gov.au/reporting/.
Nopens I., Benedetti L., Jeppsson U., Pons M.-N., Alex J., Copp J. B., Gernaey K. V., Rosen C., Steyer J.-P. and Vanrolleghem P. A. (in press). Benchmark simulation model no 2: finalisation of plant layout and default control strategy. *Water Sci. Technol.*, in press.
Nopens, I., Batstone, D.J., Copp, J.B., Jeppsson, U., Volcke, E., Alex, J., Vanrolleghem, P.A., (2009). An ASM/ADM model interface for dynamic plant-wide simulation. *Water Res.* **43**(7), 1913-1923.
Oennerth T.B., Nielsen M.K., and Stamer C. (1996). Advanced computer control based on real and software sensors. *Water Sci. Technol.*, **33**(1), 237-245.
Olsson G., Nielsen M.K., Yuan Z., Ynggaard-Jensen A., Steyer J.P. (2005). *Instrumentation, Control and automation in wastewater systems*. IWA Publishing, London, UK.
Pagilla K., Shaw A., Kunetz T. and Schiltz M. (2009). A Systematic spproach to establishing carbon footprints for wastewater treatment plants. *In:* Proceedings of WEFTEC 2009, Orlando, Florida, USA, October 10-14, 2009.
Stare A., Vrecko D., Hvala N. and Strmcnik S. (2007). Comparison of control strategies for nitrogen removal in an activated sludge process in terms of operating costs: A simulation study. *Water Res.* **41**(9), 2004-2014.
von Schulthess R. and Gujer W. (1996). Release of nitrous oxide (N2O) from denitrifying activated sludge: Verification and application of a mathematical model. *Water Res.* **30** (3), 521-530.
Zhao H., Isaacs SH., Soeberg H. and Kummel M. (1995). An analysis of nitrogen removal and control strategies in an alternating activated-sludge process. *Water Res.* **29**(2), 535-544.