Cost-efficient control of wastewater treatment plants to reduce greenhouse gas emissions

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Abstract: This research investigates the potential of improved wastewater treatment plant control for the cost-efficient reduction of greenhouse gas (GHG) emissions, providing a detailed exploration of the decision variable search space. Key operational parameters identified using global sensitivity analysis are sampled to provide sets of values for testing in two pre-defined control strategies. It is shown that significant reductions in emissions and costs can be realized by improved selection of parameter values. The importance of considering GHGs when selecting a control strategy is also highlighted, as the two strategies tested are shown to produce effluent of a similar quality but with significantly different emissions and operating costs.

Keywords: control; global sensitivity analysis; greenhouse gas; operation; wastewater treatment

Introduction

Global warming is an internationally recognised problem and the significance of greenhouse gas (GHG) emissions resulting from wastewater treatment processes has been highlighted in numerous studies (e.g. Rothausen and Conway 2011). Water companies are tasked with reducing their GHG emissions to assist in reaching national targets, yet they must remain economically viable and ensure adequate treatment standards are maintained.

Appropriate wastewater treatment plant (WWTP) operation can contribute greatly to the reduction of GHG emissions (Gori et al. 2011) and it has been shown that significant emission reductions can be realized by the implementation of automatic control (Flores-Alsina et al. 2011). Previous studies (Flores-Alsina et al. 2014, Guo et al. 2012b) have explored the effects of implementing a selection of different control strategies and of using different setpoints; however, conclusions drawn regarding WWTP control and performance are based on only a small number of modelled scenarios. A thorough investigation into the benefits achievable and required trade-offs is therefore required.

Multi-objective optimisation has been used to obtain a clearer picture of the trade-offs between GHG emissions, operational costs and effluent quality (Sweetapple et al. 2014). However, the results cannot be used to prescribe a specific control strategy that will provide a cost efficient reduction of GHG emissions, due to the use of a short simulation period and the potential for reduced performance when evaluated over a full year.

The objective of this work is to investigate the potential of improved control strategy design and parameterisation for the reduction of GHG emissions from WWTPs, taking into account the need to produce an acceptable effluent quality whilst remaining cost efficient and considering long term performance. Global optimisation of control strategies based on dynamic performance over an extended period is challenging due to the high computational demand of mechanistic WWTP models and large number of model evaluations required. In this study, therefore, two control strategies are considered and operational parameters to which GHG emissions, operational costs and effluent quality are found to be most sensitive are sampled using the factorial sampling design approach to provide a search of the decision variable space.

Material and Methods

Wastewater treatment plant model

Wastewater treatment processes are simulated in BSM2-e (Sweetapple et al. 2013), a version of the Benchmark Simulation Model No. 2 (BSM2) (Jeppsson et al. 2007) modified for modelling of dynamic GHG emissions. The plant consists of a primary clarifier, five activated sludge reactors, a secondary settler, a sludge thickener, an anaerobic digester and a dewatering unit. Simulations are carried out as in BSM2, using 200 days of constant influent to allow the model to reach steady state then 609 days of dynamic influent, of which the last 364 are used for evaluation.

Sources of GHG emissions modelled include: aerobic substrate utilisation, biomass decay and denitrification in the activated sludge reactors, leakage and combustion of biogas from the anaerobic digester, stripping of methane (CH_4) from solution in the dewatering unit, generation of energy imported, manufacture of chemicals, offsite degradation of effluent, and transport and offsite degradation of sludge. Nitrous oxide (N_2O) emissions associated with nitrification are omitted due to a lack of consensus on suitable modelling techniques (models exist but have been found unable to accurately and consistently reproduce experimental data (Sperandio et al. 2014)). It is recommended that future work investigate the impact of control strategies developed in this study on such emissions, since the net impact on emissions may be less desirable than anticipated.

Emissions are reported in units of kg CO_2e/m^3 treated wastewater, using global warming potentials of 21 and 310 for CH_4 and N_2O respectively (IPCC 1996). Operational costs and effluent quality are assessed using an operational cost index (OCI) and effluent quality index (EQI) respectively, as defined by Jeppsson et al. (2007), and compliance is assessed with regard to the Urban Waste Water Treatment Directive requirements (European Union 1991). It must be noted that the results obtained from this model are not directly comparable with those from BSM2 due to alteration of the activated sludge model to include four-step denitrification.

Control strategies

Two different arrangements of sensors, controllers and actuators providing dissolved oxygen (DO) control are investigated, since it is known that DO control affects both operational costs (due to the impact on energy consumption (e.g. Åmand and Carlsson 2012)) and GHG emissions (e.g. Aboobakar et al. 2013). Sensitivity analysis has also shown aeration intensities in the aerobic activated sludge reactors to be key control handles for the reduction of GHG emissions, operational costs and effluent pollutant loadings (Sweetapple et al. in press).

Firstly, the BSM2 default closed loop (DCL) control strategy (Nopens et al. 2010) is implemented; and secondly, one in which the DO spatial distribution is controlled using three independent control loops (3-DO control strategy). Both are illustrated in Figure 1. The BSM2 DCL control strategy with default parameter values (Nopens et al. 2010) represents the base case. The 3-DO control strategy has previously been shown to provide an acceptable effluent quality at an acceptable cost (Vanrolleghem and Gillot 2002) and Guo et al. (2012a) found this strategy to provide the greatest reduction in N_2O emissions. Given that N_2O is a significant contributor to total GHG emissions from wastewater treatment and the source with greatest potential for improvement (Sweetapple et al. in press), it is thought that this control strategy may provide cost-efficient reduction of emissions. Provisionally, a setpoint of 1 g O_2/m^3 and offset of 200 d^{-1} (Vanrolleghem and Gillot 2002) is set for every controller in this strategy.

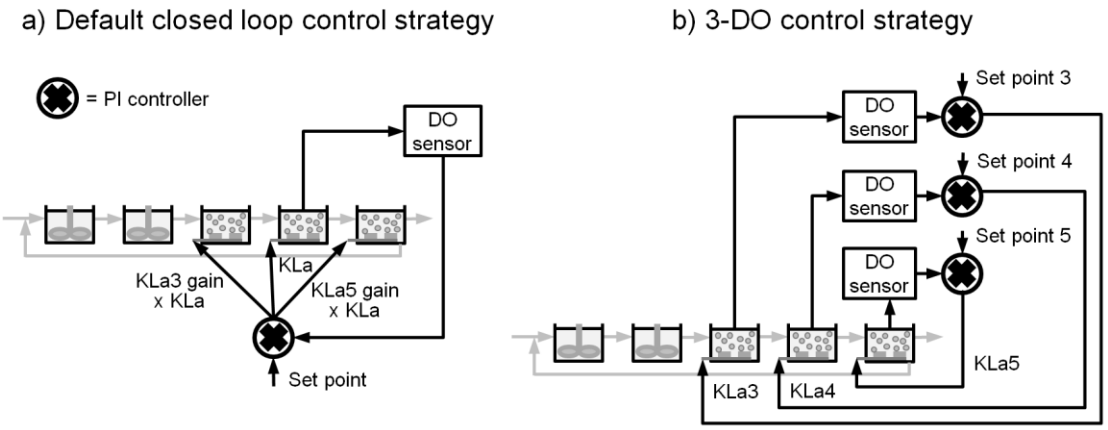

Figure 1 Control of the activated sludge unit in: a) the DCL control strategy; and b) the 3-DO control strategy.

Selection of sensitive control handles for further adjustment in this study is based on the results of global sensitivity analysis (GSA) using Sobol's method (Sobol 2001), which enables identification of significant individual and interaction effects (Sweetapple et al. in press) as shown in Figure 2.

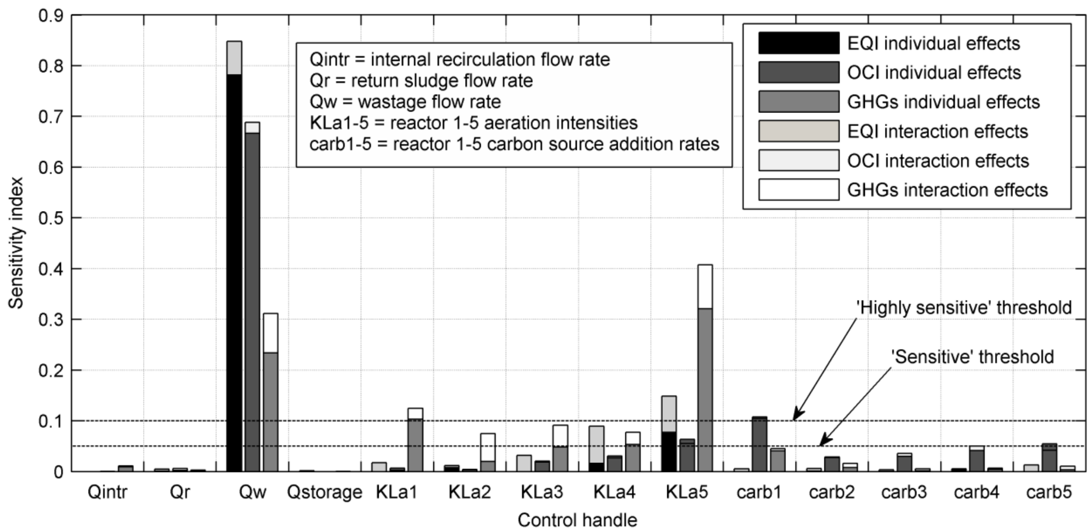

Figure 2 Sensitivity indices for WWTP operational parameters, calculated using Sobol's method, based on EQI, OCI and GHG emissions. Based on results of Sweetapple et al. (in press).

GHG emissions, OCI and EQI are all shown to be highly sensitive to wastage flow rate (*Qw*) and Flores-Alsina et al. (2011) has shown significant reduction in GHG emissions to be achievable by adjustment of *Qw* to change the sludge retention time (SRT). As WWTPs are subject to seasonal effects, optimal controller setpoints differ throughout the year (Stare et al. 2007) and different wastage flow rates may be implemented in order to maintain sufficient biomass in the system during winter months (e.g. Flores-Alsina et al. 2011). In this research, it is decided to implement three different wastage rates (with values to be decided) in both control strategies throughout the year, dependent on temperature: Qw_{low} (when $t \leq 13.2$°C), Qw_{medium} (when 13.2°C < $t \leq 16.8$°C) and Qw_{high} (when $t > 16.8$°C). Limits are set so as to provide three equal width bands, based on the observed annual temperature range.

Decision variable sampling

Factorial sampling is selected as it can provide good coverage of the search space within a relatively small number of simulations; Monte Carlo sampling, despite providing greater coverage, is not suitable due to the time taken for each model evaluation.

A 10-level factorial sampling design is used to generate a set of values for Qw_{low}, Qw_{medium} and Qw_{high} within the range 93.5 to 506.5 m^3/d for the DCL control strategy. This contains 1,000 samples, reduced to 220 when instances in which $Qw_{low} > Qw_{medium}$ or $Qw_{medium} > Qw_{high}$ are removed. Samples evaluated in the 3-DO control strategy are restricted to 84 in which $Qw_{low} > 139.5$ m^3, since these were consistently found to produce a compliant effluent in the DCL control strategy.

Given that the control handle *KLa5* is also shown to be key for the reduction of GHG emissions and is classified as sensitive or highly sensitive based on all three performance indicators (Sweetapple et al. in press), the DO set point for reactor 5 in the 3-DO control strategy is also considered as a decision variable. This is sampled within the range 0.5 to 2.5 g O_2/m^3 using 5-level factorial sampling for each combination of wastage flow rates.

Results and Discussion

Wastage flow rate adjustment

Performance of control strategies with adjusted wastage flow rates which produce a compliant effluent is shown in Figure 3. It is observed that implementation of different combinations of Qw values can enable a reduction of both GHG emissions and OCI simultaneously whilst maintaining compliance in both control strategies.

In the DCL control strategy, GHG emissions can be reduced by up to 6.0% with respect to the base case whilst also reducing the OCI by 2.3%. The lowest emission solution uses a constant wastage flow rate of 185.3 m^3/d – corresponding to a significantly longer SRT than in the base case (28 days mean compared with 15 days). The predominant source of reduction in operating costs is the reduction of sludge produced for disposal, not reduction in pumping costs as may be expected. Energy costs actually increase due to increased aeration requirements to maintain the specified setpoint. Reduction in GHG emissions associated with a reduction in energy required for pumping is also negligible (0.1% contribution). Change in N_2O emissions from the activated sludge reactors provide 131% of the net reduction in emissions whilst non-N_2O emissions from the activated sludge reactors provide -61% (i.e. they increase). This supports the observation of Flores-Alsina et al. (2011) that a high SRT increases direct non-N_2O emissions from the bioreactor and indirect emissions resulting from electricity use.

The reduction in GHG emissions and OCI achievable by adjustment of wastage flow rate in the default open loop control strategy also corresponds with an increase in EQI (although all solutions presented remain compliant, and in some instances the

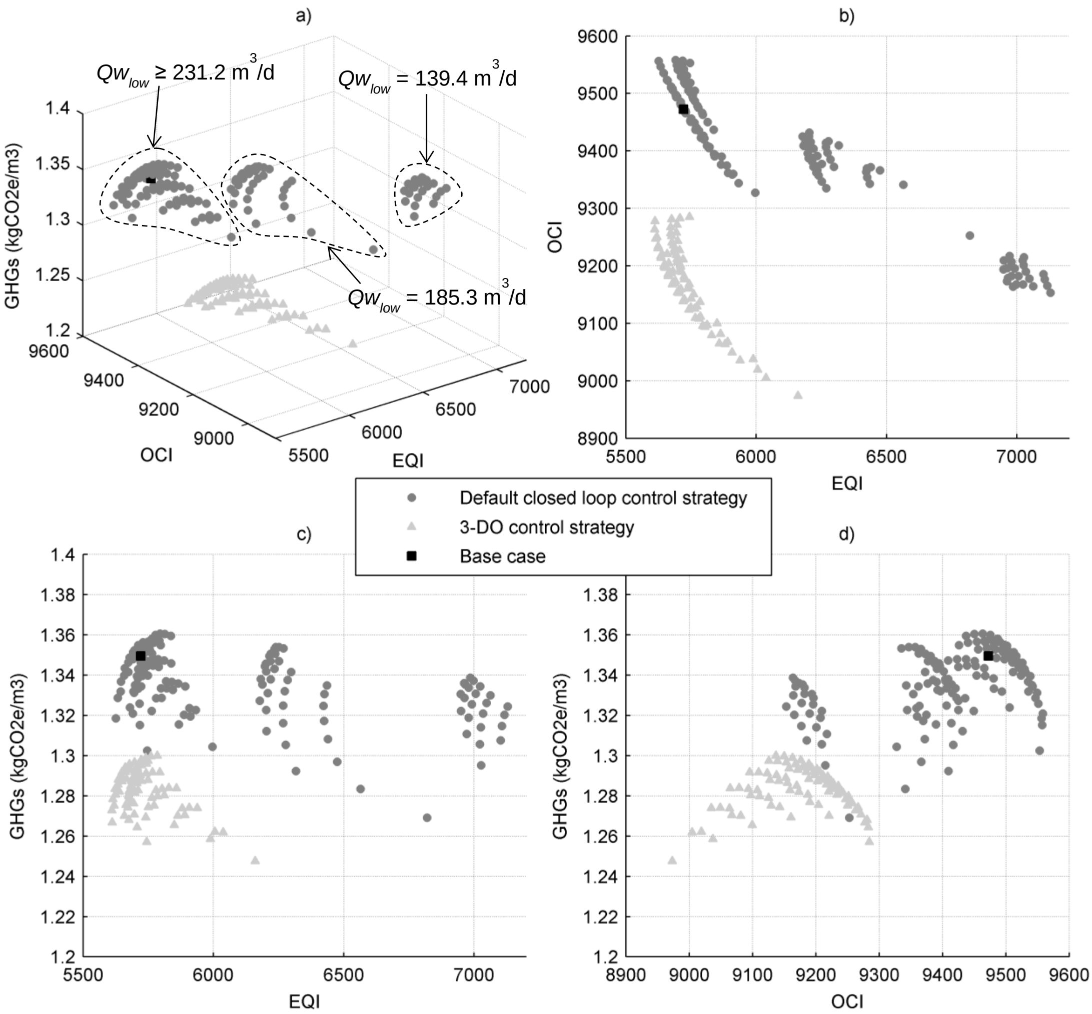

Figure 3 WWTP performance with adjusted control strategy wastage flow rates (compliant solutions only).

impact on effluent quality is minor); all solutions which reduce the EQI increase operational costs. GHG emissions and EQI can be reduced simultaneously through improved control of wastage flow rates, but this is at the expense of OCI.

Solutions in the 3-DO control strategy have significantly lower GHG emissions and operating costs than those with a comparable effluent quality in the DCL control strategy. This highlights the importance of evaluating a range of alternative control options and suggests that, of the two studied, the 3-DO control strategy offers superior performance with regard to GHG emissions, operational costs and effluent quality. It also supports recommendation that implementation of the 3-DO control strategy would be economically wise (Vanrolleghem and Gillot 2002).

Using the 3-DO control strategy, an equivalent effluent quality to that of the base case can be maintained whilst reducing GHG emissions by 6.3% and also cutting operational costs by 2.0%, by implementing wastage flow rates of 231.2, 231.2 and 277.1 m^3/d for Qw_{low}, Qw_{medium} and Qw_{high} respectively. This solution provides a mean SRT of 22 days – again, significantly greater than that of the base case.

It may be thought that selection of a control strategy in which energy recovery from biogas combustion is reduced would be undesirable in terms of both operational costs and GHG emissions. This specific solution, however, exhibits a net decrease in both

OCI and GHG emissions despite enabling less energy recovery than the base case control strategy: the increase in operational costs as a result of reduced energy recovery is less than the cost saving resulting from reduced sludge production, and the total indirect emissions resulting from net energy import decrease due to the reduction in energy required for pumping and aeration.

It is also found that implementing solutions providing a shorter SRT can be of benefit with regard to cost and emissions: the solution providing the greatest emission reduction (7.6%) in the 3-DO control strategy has a constant *Qw* value of 506 m^3/d (upper limit of range tested) and a mean SRT of 11 days and provides a reduction in both N_2O *and* non-N_2O emissions from the activated sludge unit. However, this also causes a 7.7% increase in EQI.

These contrasting combinations of *Qw* values shown to provide a reduction in net GHGs with no additional operational costs demonstrate that an emission reduction is achievable with different approaches to SRT control, each of which affects different sources of emissions. Given the trade-off in EQI observed with a high wastage flow rates, however, it is suggested that a high SRT solution may be preferable. Furthermore, emissions not included in this study are likely to be significant in low SRT solutions: for example, N_2O emissions from biological hydroxylamine oxidation occur mainly at high NH_4^+ and low NO_2^- concentrations (Wunderlin et al. 2012), which are likely to be present with a low SRT.

Dissolved oxygen setpoint adjustment

Figure 4 shows that adjustment of DO concentrations in the final aerobic reactor (by manipulation of the DO setpoint) in addition to *Qw* enables the development of solutions which further improve upon the base case GHG emissions and OCI whilst having negligible impact on effluent quality. Conversely, selection of too high a setpoint is found to increase GHG emissions and OCI.

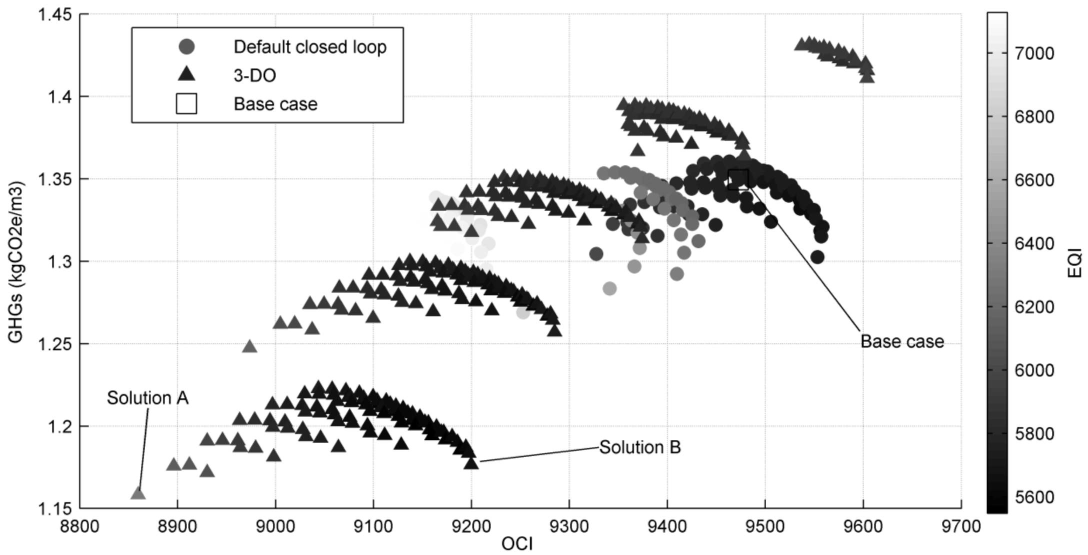

Figure 4 WWTP performance with adjusted reactor 5 DO setpoint in the 3-DO control strategy and adjusted wastage flow rates in both (compliant solutions only); colour denotes EQI, with a darker shade representing a better quality effluent.

The cluster of solutions found to perform best with regard to OCI and GHG emissions all have a reduced DO setpoint of 0.5 g O_2/m^3. To enable analysis of the effects of *Qw* adjustments on different contributors to operational costs and GHG emissions, two solutions in this cluster are compared in Table 1: Solution A provides the lowest GHG emissions and OCI but at the expense of effluent quality, solution B provides a smaller (but still significant) emission and cost reduction with regard to the base case but with no loss in effluent quality.

Table 1 Comparison of solutions, with percentage contribution of component change to total change in performance indicator in brackets. Only GHG and OCI components of interest are shown. Components worsened with respect to the base case are highlighted.

Solution		Base case	A	B
Aeration control		DCL	3-DO	3-DO
Mean SRT (days)		15.5	11.4	23.2
GHG components (kg CO_2e/m^3)	N_2O from activated sludge	0.50	0.34 (83%)	0.31 (111%)
	Non-N_2O from activated sludge	0.39	0.35 (20%)	0.43 (-24%)
	Pumping energy	0.01	0.01 (0%)	0.01 (0%)
	Aeration energy	0.05	0.04 (4%)	0.05 (1%)
	Sludge transportation and degradation	0.05	0.06 (-1%)	0.05 (2%)
OCI components (-)	Energy use	5560	4975 (95%)	5369 (70%)
	Energy recovery	-6425	-6693 (44)	-6089 (-123%)
	Sludge for disposal	7938	8178 (-39%)	7519 (153%)
Performance indicators	Total GHGs (kg CO_2e/m^3)	1.35	1.16	1.18
	OCI	9472	8860	9200
	EQI	5722	6298	5670

As with the DCL control strategy, a high SRT solution results in an increase in non-N_2O emissions from the activated sludge but this is offset by the decrease in N_2O emissions to give a net reduction.

In solution A, the cost reduction is achieved primarily through a reduction in energy use and an increase in energy recovery. Solution B, however, provides significantly less energy recovery than the base case yet still offers a reduction in overall operational costs and GHG emissions and a greatly improved effluent quality. This again suggests that solutions providing the greatest energy recovery from biogas production may not necessarily be the most desirable in terms of net benefits.

Conclusions

This study has investigated WWTP performance with regard to GHG emissions, operational costs and effluent quality under two different control strategies and with a range of wastage flow rates and DO setpoints. It is found that independent control of aeration in each aerated activated sludge reactor, in particular when using a low reactor 5 DO setpoint, enables significant reduction in both GHG emissions and operational costs whilst maintaining a high effluent quality. However, in both control strategies analysed, significant improvements can be achieved through better control of wastage flow rates alone.

The results emphasise the importance of considering the effects of emission reduction measures on emissions from a range of different sources rather than focussing on just one high priority source. Increasing the SRT, for example, can result in emission and cost reduction but direct non-N_2O emissions are increased. Furthermore, it is suggested that developing control strategies to provide the greatest possible energy recovery may not always be necessary (or desirable) with regard to reducing GHG emissions and operational costs, since the effects of reduced energy recovery can be offset by the reduction in cost and emissions associated with sludge disposal, and a greater effluent quality may be achieved.

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