Study on sensitive analysis criteria for activated sludge models combined with settling model

J. R. Kim* • J. H. Ko* • K. S. Choi** • S. I. Lee*** • C. W. Kim*
* Dept. of Environmental Engineering, Pusan National University, Korea
** Dept. of Marine Environmental Engineering, Kyeongsang National University, Korea
*** Dept. of Environmental Engineering, Chungbuk National University, Korea

Abstract

The purpose of this paper was to propose proper sensitivity analysis criteria which can minimize calibration efforts and produce reliable effluent quality predictions. ASM1 and ASM3 parameter sensitivity (in combination with a one-dimensional settling model) was analyzed by various criteria based on the step variation of single parameters (SVM) or random variations of all parameters (RVM), using the *IWA Simulation Benchmark* (Copp *et al.* 2002). SVM was not significantly affected by the analysis conditions and it produced reliable ΔEQ values in every case. Moreover, it was the easiest and simplest methodology. Once selected the parameters were estimated with a genetic algorithm. It was concluded that SVM was the best sensitivity analysis criteria for both ASM1 and ASM3 in this case.

Key Words: Activated sludge model, genetic algorithm, sensitivity analysis, Simulation Benchmark

INTRODUCTION

The complicated and nonlinear characteristics of the activated sludge models (ASMs) make it very difficult to identify the system behavior. Parameter estimation is essential for process modeling, but it generally requires lots of time and effort. It has been reported that the success and failure of a model application are strongly related to the cost for stoichiometric and kinetic parameter estimation (Sollfrank and Gujer, 1991; Ko *et al.*, 2001).

Sensitivity analysis is an essential procedure for selecting significant parameters which can have serious effects on process behavior, *prior* to numerical parameter optimization. The aim of this study was to understand the sensitivity of ASM1 and ASM3 parameters and to suggest a criteria for selecting sensitive parameters. Even though a sedimentation process might have an impact on the biological process, the settling model has been commonly ignored during previous sensitivity analysis research. In this paper, the sensitivity of settling model parameters also has been analyzed.

METHODS

Target process and models

The target process was the denitrifying layout of the IWA *Simulation Benchmark* (Copp *et al.*, 2002). *Simulation Benchmark* adopts ASM1 and a one-dimensional settling model (Takacs *et al.*, 1991) for biological reactors and the clarifier, respectively. In this study, ASM3 was also included and sensitivity analysis of the parameters was performed.

Effluent Quality (EQ) index for sensitivity indexes and objective function calculation

Selection of sensitive parameters might be influenced by the sensitivity index (SI) calculation method (Saltelli *et al.*, 2000). In this study, eleven SI calculation methods were examined (Fig. 1). Sensitivity indices were based on Effluent Quality (EQ) as defined by the IWA Task Group. Slight modifications had to be made for calculating the ASM3 EQ (Kim *et al.* 2004).

The difference in EQ (ΔEQ) was calculated as below;

$$\Delta EQ = EQ_{\mathrm{Ref}} - EQ_{\mathrm{Var}} \qquad \text{(Eq. 1)}$$

where EQ_{Ref} = EQ calculated with reference parameters values
EQ_{Var} = EQ calculated with varied parameters values

After selecting the parameters, they were estimated with a genetic algorithm (GA) aimed at minimizing ΔEQ.

Sensitive parameter selection criteria

The criteria for selecting sensitive parameters is shown in Fig. 1. Each parameter was changed from 50 to 200% of its reference value. The parameters were changed by 10% for the step variation method (SVM). For the random variation method (RVM), 2,000 simulations were conducted with randomly selected sets of parameters.

Tab. 1. Values of insensitive parameters according to the type of model.

	ASM1		ASM3	
	Reference simulation	Estimation step	Reference simulation	Estimation step
Ideal case	*Simulation Benchmark* defaults (Copp *et al.*, 2002)	*Simulation Benchmark* defaults	ASM3 defaults (Henze *et al.*, 2000)	ASM3 defaults
Practical cases	ASM1 defaults (Henze *et al.*, 2000)	*Simulation Benchmark* defaults	Tuned for Bio-P Module (Rieger *et al.*, 2001)	ASM3 defaults

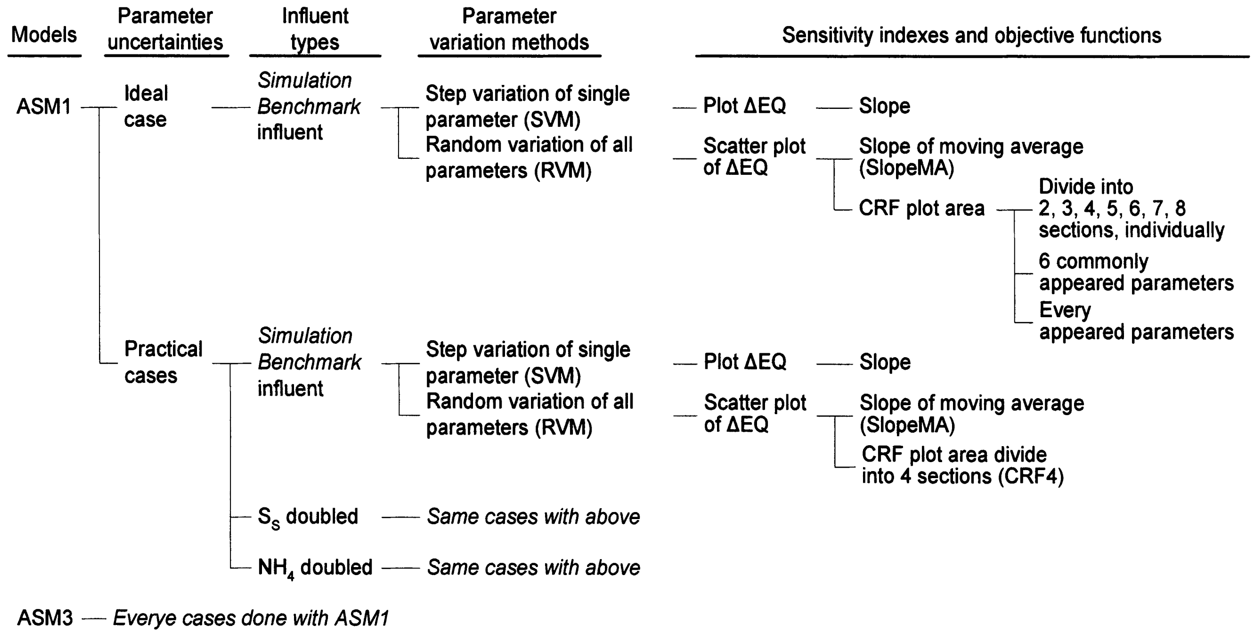


Fig. 1. Tested sensitivity analysis criteria.

Parameter estimation

After parameters were classified into sensitive or insensitive, only the most sensitive parameters were optimized with GA (Kim *et al.*, 2002). Carroll's GA was applied (Kim *et al.* 2004, Yang *et al.*, 1998) and the applied genetic operator was a two-member tournament selection, uniform crossover, flip and creep mutation, elitism and niching (Goldberg, 1989).

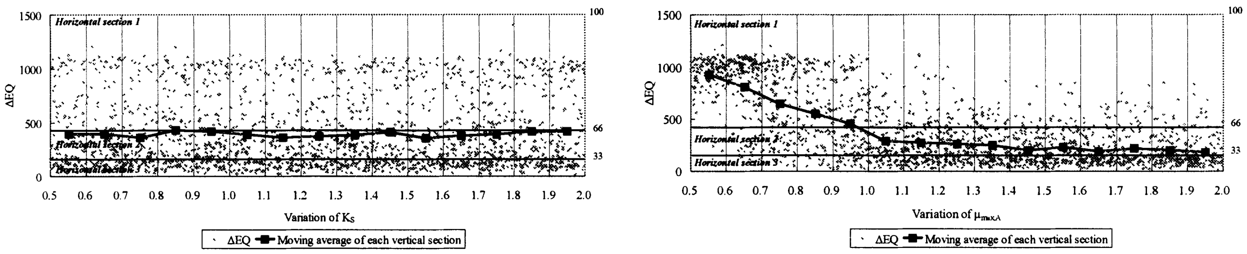
RESULTS AND DISCUSSTION

Sensitivity analysis

Step variation of single parameter. The impact on EQ was plotted against the parameter value and the greater the impact ,the higher the sensitivity. The most sensitive five parameters of ASM1 and ASM3 selected by SVM were as following:

- ASM1 : Y_H, b_H, $\mu_{max,A}$, $K_{O,A}$, b_A
- ASM3 : $Y_{STO,NO}$, $Y_{H,NO}$, $\mu_{max,A}$, η_{NO}, b_A

Random variation of all parameters. Calculated ΔEQs versus the varied parameters were presented as a scatter plot. If a parameter was insensitive, dots distribution inside each vertical section was uniform, implying that the effect from the variation of that parameter was not significant and could be compensated by the variation in other parameters (Fig.2a) The sensitive parameters resulted in a different distribution of dots (Fig.2b). For quantifying the sensitivity, two different methods were used; 1) slope of moving average in each vertical section as shown in Fig. 2a and 2b, 2) area of cumulative relative frequency (CRF) (data not shown). K_S and $\mu_{max,A}$ were selected as typical examples of insensitive and sensitive parameters, respectively.



(a) (b)

Fig. 2. Sensitivity parameter selection criteria based on RVM;
(a), (b) scatter plot and slope of moving averaged K_S and $\mu_{max,A}$ in ASM1, respectively

Selected sensitive parameters and simulation results in the ideal case

Sensitive parameters of ASM1. SVM identified Y_H, b_H, $\mu_{max,A}$, b_A and $K_{O,A}$, as being sensitive and RVM identified Y_H, b_H, $\mu_{max,A}$, b_A, k_h (for ASM1) and v_0 and r_h (for the one-dimensional settling model). Y_H, $\mu_{max,A}$, and r_h were identified by RVM in every case, and v_0 was identified in all cases except SlopeMA. RVM identified one or two settling parameters each time, but those did not show high sensitivity with SVM (Tab. 2).

Sensitive parameters of ASM3. SVM identified $Y_{STO,NO}$, $Y_{H,NO}$, $\mu_{max,A}$, b_A and η_{NO} as being sensitive, while RVM identified $Y_{H,O2}$, $i_{N,Xs}$, $\mu_{max,A}$, b_A, $K_{O,A}$, r_h and v_0. Just like in ASM1, one or two settling parameters were identified by RVM in each case except SlopeMA and CRF8 both of which did not identify any settling parameters. The nitrogen content of X_S ($i_{N,Xs}$), was identified by RVM and it was reasoned that this parameter had a large impact on the nitrogen concentration to be nitrified. No criteria identified b_H and k_h as sensitive which is in contrast to the ASM1 results.

Tab. 2. Selected sensitive parameters and simulation results at ideal case.

ASM1

Analysis methods: Variation method	Analysis methods: Sensitivity Index	Highly sensitive parameters: Stoichiometric	Highly sensitive parameters: Kinetic	Highly sensitive parameters: Settling	ΔEQ	Absolute error (mg/L): COD	Absolute error (mg/L): NH_4	Absolute error (mg/L): NO_3	Absolute error (mg/L): TSS
SVM		Y_H,	b_H, $\mu_{max,A}$ b_A, $K_{O,A}$		0.57	0.45	0.01	0.02	0.33
RVM	SlopeMA	Y_H,	$\mu_{max,A}$, b_A, $K_{O,A}$,	r_h	0.91	0.09	0.02	0.02	0.07
	CRF2	Y_H,	$\mu_{max,A}$, b_A,	r_h, v_0	3.69	0.01	0.18	0.01	0.00
	CRF3	Y_H,	$\mu_{max,A}$, b_A,	r_h, v_0	3.69	0.01	0.18	0.01	0.00
	CRF4	Y_H,	$\mu_{max,A}$, k_h,	r_h, v_0	1.08	0.12	0.01	0.02	0.18
	CRF5	Y_H,	b_H, $\mu_{max,A}$,	r_h, v_0	4.01	0.50	0.10	0.04	0.29
	CRF6	Y_H,	$\mu_{max,A}$, k_h,	r_h, v_0	1.08	0.12	0.01	0.02	0.18
	CRF7	Y_H,	$\mu_{max,A}$, k_h,	r_h, v_0	1.08	0.12	0.01	0.02	0.18
	CRF8	Y_H,	$\mu_{max,A}$, k_h,	r_h, v_0	1.08	0.12	0.01	0.02	0.18
	Common6	Y_H,	$\mu_{max,A}$, b_A, k_h,	r_h, v_0	11.33	2.79	0.18	0.00	2.15
	Every7	Y_H,	b_H, $\mu_{max,A}$, b_A, k_h,	r_h, v_0	4.72	0.45	0.15	0.02	0.42

ASM3

		Stoichiometric	Kinetic	Settling					
SVM		$Y_{STO,NO}$, $Y_{H,NO}$,	$\mu_{max,A}$, b_A, η_{NO}		2.66	0.02	0.12	0.02	0.01
RVM	SlopeMA	$Y_{H,O2}$, $i_{N,Xs}$,	$\mu_{max,A}$, b_A, $K_{O,A}$		0.76	0.04	0.02	0.01	0.03
	CRF2	$Y_{H,O2}$, $i_{N,Xs}$,	$\mu_{max,A}$,	r_h, v_0	1.76	0.05	0.02	0.06	0.10
	CRF3	$Y_{H,O2}$, $i_{N,Xs}$,	$\mu_{max,A}$, b_A,	v_0	0.81	0.21	0.01	0.02	0.08
	CRF4	$i_{N,Xs}$,	$\mu_{max,A}$, b_A,	r_h, v_0	1.58	0.26	0.02	0.04	0.22
	CRF5	$i_{N,Xs}$,	$\mu_{max,A}$, b_A,	r_h, v_0	1.58	0.26	0.02	0.04	0.22
	CRF6	$Y_{H,O2}$, $i_{N,Xs}$,	$\mu_{max,A}$, b_A,	v_0	0.81	0.21	0.01	0.02	0.08
	CRF7	$i_{N,Xs}$,	$\mu_{max,A}$, b_A, $K_{O,A}$	v_0	2.22	0.14	0.05	0.03	0.11
	CRF8	$Y_{H,O2}$, $i_{N,Xs}$,	$\mu_{max,A}$, b_A, $K_{O,A}$		0.87	0.03	0.03	0.01	0.02
	Common6	$Y_{H,O2}$, $i_{N,Xs}$,	$\mu_{max,A}$, b_A,	r_h, v_0	1.14	0.25	0.02	0.00	0.20
	Every7	$Y_{H,O2}$, $i_{N,Xs}$,	$\mu_{max,A}$, b_A, $K_{O,A}$	r_h, v_0	1.65	0.38	0.18	0.13	0.19

Tab. 3. Selected sensitive parameters and simulation results at practical cases.

ASM1

Analysis methods: Sensitivity Index	Influent type	Highly sensitive parameters: Stoichiometric	Highly sensitive parameters: Kinetic	Highly sensitive parameters: Settling	ΔEQ	Absolute error (mg/L): COD	Absolute error (mg/L): NH_4	Absolute error (mg/L): NO_3	Absolute error (mg/L): TSS
SVM	S. B. default	Y_H,	b_H, $\mu_{max,A}$, b_A, $K_{O,A}$		2.09	0.13	0.02	0.02	0.62
	S_S doubled	Y_H,	b_H, $\mu_{max,A}$, b_A, $K_{O,A}$		2.52	1.48	0.03	0.02	0.08
	NH_4 doubled	Y_H,	b_H, $\mu_{max,A}$, b_A, $K_{O,A}$		11.62	0.31	0.07	0.45	0.43
RVM-SlopeMA	S. B. default	Y_H,	$\mu_{max,A}$, b_A, $K_{O,A}$,	r_h	3.03	0.78	0.01	0.05	0.51
	S_S doubled	Y_H,	$K_{O,H}$, $\mu_{max,A}$, $K_{O,A}$,	v_0	1.13	0.37	0.01	0.01	0.12
	NH_4 doubled	Y_H,	$\mu_{max,A}$, b_A, $K_{O,A}$,	v_0	8.57	0.92	0.12	0.22	0.42
RVM-CRF4	S. B. default	Y_H,	$\mu_{max,A}$, k_h,	r_h, v_0	6.13	0.26	0.23	0.01	0.94
	S_S doubled	Y_H,	b_H, $\mu_{max,A}$,	r_h, v_0	17.75	0.58	0.03	0.37	8.66
	NH_4 doubled	Y_H,	$\mu_{max,A}$, k_h,	r_h, v_0	11.16	0.30	0.09	0.33	1.23

ASM3

		Stoichiometric	Kinetic	Settling					
SVM	S. B. default	$Y_{STO,NO}$, $Y_{H,NO}$,	$\mu_{max,A}$, b_A, η_{NO}		0.53	0.02	0.02	0.01	0.01
	S_S doubled	$Y_{STO,O2}$, $Y_{H,O2}$, $Y_{H,NO}$,	$\mu_{max,A}$,	r_h	2.40	0.35	0.06	0.01	0.34
	NH_4 doubled	$Y_{STO,NO}$, $Y_{H,O2}$, $Y_{H,NO}$,	$\mu_{max,A}$, b_A		0.47	0.00	0.00	0.01	0.08
RVM-SlopeMA	S. B. default	$Y_{H,O2}$, $i_{N,Xs}$,	$\mu_{max,A}$, b_A, $K_{O,A}$		5.41	0.86	0.25	0.15	0.76
	S_S doubled	$Y_{STO,O2}$, $Y_{H,O2}$, $i_{N,Xs}$,	$\mu_{max,H}$, $\mu_{max,A}$		0.91	0.33	0.00	0.00	0.27
	NH_4 doubled	$Y_{H,O2}$, f_{Xi},	$\mu_{max,A}$, b_A, $\eta_{NO,END}$		2.83	0.03	0.10	0.04	0.05
RVM-CRF4	S. B. default	$i_{N,Xs}$,	$\mu_{max,A}$, b_A,	r_h v_0	19.82	0.02	0.65	0.34	0.01
	S_S doubled	$Y_{STO,O2}$, $Y_{H,O2}$,	$\mu_{max,A}$, $K_{O,A}$,	r_h	2.19	0.56	0.00	0.03	0.37
	NH_4 doubled		$\mu_{max,A}$, b_A,	r_h v_0, r_p	56.83	0.04	0.07	2.77	0.01

Selected sensitive parameters and simulation results in the practical cases

Sensitive parameters of ASM1. In the practical cases, a different set of insensitive parameter values was used for the reference simulation. Three criteria were examined at practical cases; SVM, SlopeMA and CRF4. In the practical case, SVM identified precisely the same parameters as identified in the ideal case. This suggests that SVM is not significantly affected by influent

type and the insensitive parameter values and further suggests that this methodology is valid for ASM1. This contrasts the SlopeMA and CRF4 results which identified different parameters depending on the simulation setup (Tab. 3).
Sensitive parameters of ASM3. The various simulation conditions identified a total of 15 sensitive parameters as compared to 9 for the ASM1 simulations. In this case, different parameters were selected and no criteria exhibited consistent results.

Parameter estimation with GA and validation

With the sensitive parameters identified, a genetic algorithm was then used to estimate the values of the sensitive parameters to see if the genetic algorithm could find the solution and minimize ΔEQ. Previous work (Kim *et al.* 2002) suggested that the use of a genetic algorithm was a suitable choice for finding optimal parameter values. However in this case, finding the solution is complicated by the fact that the IWA Simulation Benchmark quantity, EQ, is a composite variable composed of carbon and nitrogen state variables meaning that it could be possible to minimize ΔEQ (or even find a ΔEQ of zero) with a different combination of nitrogen and carbon species. A list of sensitive parameters, ΔEQ and absolute errors of effluent COD, NH_4, NO_3 and TSS according to sensitivity analysis criteria are shown in Tab. 2 and 3 under ideal and practical cases, respectively.

The highest ΔEQs (ignoring Common6 and Every7) were 4.01 and 2.66 for ASM1 and ASM3 respectively in the ideal case. These relatively high values were attributed to an NH_4^+-N and NO_{3-}-N prediction error less than 0.2 mg/L. For practical purposes an error of this magnitude is negligible, but it is amplified in this case by the IWA weighting factor of 20 applied to nitrogenous species. It was therefore concluded that SVM combined with a well-tuned GA is a suitable approach for sensitivity analysis and parameter estimation.

CONCLUSIONS

Various sensitivity analysis criteria were examined in an effort to minimize calibration efforts and produce reliable prediction results. For ASM1, the step variation of single parameters (SVM) proved to be any acceptable approach and provided similar results regardless of the simulation conditions. In previous research, $K_{O,A}$ and b_A were regarded as insensitive, but in this case those parameters showed high sensitivity. Other criteria based on random variation of all parameters (RVM) exhibited different sets of sensitive parameters in each case demonstrating that SVM was the better approach. For ASM3, no criteria exhibited consistent results and no conclusion could be reached about which ASM3 parameters were the most sensitive. But, it should be noted that SVM presented reliable ΔEQ values at every influent condition. Moreover, it was the simplest methodology. Therefore, it is concluded that SVM is a reasonable approach for both ASM1 and ASM3.

AKNOWLEDGEMENT

This study was financially supported by Korea Science and Engineering Foundation (project No. R01-2003-000-10714-0), Regional Research Center-Institute for Environmental Technology and Industry (RRC-IETI, project No. R12-1996-015-06001-0 & R12-1996-015-06002-0), and Pusan National University (Post-Doc. program 2004).

REFERENCES

Copp J. B., Spanjers, H. and Vanrolleghem P. A. (2002) Respirometry in Control of the Activated Sludge Process: Benchmarking Control Strategies, IWA Scientific and Technical Report No. 11, edited by John B. Copp, Henri Spanjers & Peter Vanrolleghem. IWA Publishing, London UK. (192 pages) ISBN 19-002-2251-5

Goldberg D. E. (1989). Genetic algorithms in search, Optimization and machine learning. Addison-Wesley, Reading, Mass, pp. 412.

Henze M., Gujer W., Mino T. And van Loosdrecht M. (2000). Activated sludge models: ASM1, ASM2, ASM2d and ASM3. IWA Publishing.

Kim S. H., Lee H. J., Kim J. R., Kim C. W., Ko J. H., Woo H. J. and Kim S. S. (2002). Genetic algorithms for the application of IAWQ-Activated Sludge Model No. 1. *Wat. Sci. Tech.*, 45(4-5), 405-411.

Kim J. R., Ko J. H., Lee S. H., Kim Y. J., Woo H. J., Kim C. W., (2004) Sensitive parameter selection criteria for Activated Sludge Model No. 1 and 3 combined with one-dimensional settling model, submitted at IWA Specialist Group Conference on Systems Analysis and Integrated Assessment, Watermatex 2004, 3-5 Nov. 2004, Beijing, China.

Ko J. H., Choi K. S., Woo H. J., Lee H. I. and Kim C. W. (2001). Evaluation of pH inhibition effect on activated sludge by the Pseudo Toxic Concentration (C_{PT}) Concept Model. *Wat. Sci. Tech.*, 43(7), 65-72.

Ko J. H., Woo H. J., Copp J. B., Kim, S. H. and Kim C. W. (2002). Evaluation of several respirometry-based activated sludge toxicity control strategies. *Wat. Sci. Tech.*, 45(4-5), 143-150.

Rieger L., Koch G., Kuhni M., Gujer W. and Siegrist H. (2001). The EAWAG bio-P module for Activated Sludge Model No. 3, *Wat. Res.* **35**, 3887-3903.

Sollfrank U. and Gujer W. (1991) Characterization of domestic wastewater for mathematical modelling of the activated sludge process. *Wat. Sci. Tech.*, **23**(4-6), 1057-1066.

Takjacs I., Party G. G. and Nolasco D. (1991). A dynamic model of the clarification-thickening process. *Wat. Res.*, **25**(10), 1263-1271.