Biological nutrient removal: mathematical modelling as a good strategy for control system design

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Activated sludge: 100 *plus* 1 years. New trends and perspectives
Palermo, Italy, May 11th 2015

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outline

Content

WWTP modelling

Introduce the topic of control

Define the classical control structures for an optimal EBPR

Introduce new control strategies reported in the literature

Link current models with the design of new control strategies

WWTP modelling

- Hydraulic model
  - Deduced from mass balances
  - Depends on each WWTP

- Kinetic model
  - Rate equations
  - Common for similar processes

The most common kinetic models have been developed by workgroups of the **International Water Association (IWA)** and are known as **Activated Sludge Models (ASM)**. The most used models are:

ASM1	COD + N
ASM2d	COD+ N + P
ASM3	COD + N with COD accumulation by heterotrophic organisms
ADM1	Anaerobic digestion of COD

These models take into account different types of microorganisms and numerous substrates and products.
Usually they are described using a matrix notation.

WWTP modelling

IWA - ASM2d

Henze, M.; Mujer, W.; Mino, T. and Van Loosdrecht M.C.M. (2000). *Activated sludge models ASM1, ASM2, ASM2d and ASM3: Scientific and technical report no.9.* IWA task group on mathematical modelling for design and operation of biological wastewater treatment. London, UK: IWA Publishing.

Defines three types of microorganisms:

- Heterotrophic organisms (X_H) that grow on readily biodegradable organic matter (S_F) and fermentation products (S_A)
- Autotrophs (X_A) nitrifiers that oxidise ammonium (S_{NH4}) to nitrate (S_{NO3})
- PAO (X_{PAO}), with intracellular pool of polyphosphate (X_{PP}) and organic matter (X_{PHA})

ASM2d defines a total of 19 variables and 21 processes

The model has a total of 9 stoichiometric parameters, 13 conversion factors and 45 kinetic parameters

ASM2d includes two chemical processes (precipitation and reconstitution) to model chemical P precipitation

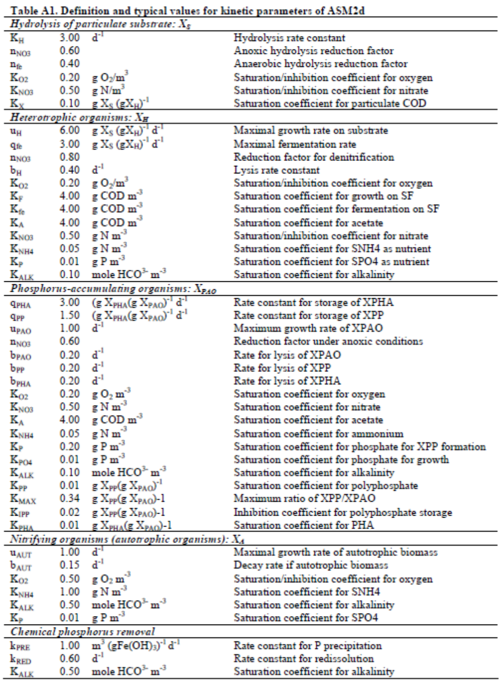

Table A1. Definition and typical values for kinetic parameters of ASM2d

Hydrolysis of particulate substrate: X_S			
K_H	3.00	d^{-1}	Hydrolysis rate constant
n_{NO3}	0.60		Anoxic hydrolysis reduction factor
n_{fe}	0.40		Anaerobic hydrolysis reduction factor
K_{O2}	0.20	$g\ O_2/m^3$	Saturation/inhibition coefficient for oxygen
K_{NO3}	0.50	$g\ N/m^3$	Saturation/inhibition coefficient for nitrate
K_X	0.10	$g\ X_S\ (gX_H)^{-1}$	Saturation coefficient for particulate COD
Heterotrophic organisms: X_H			
u_H	6.00	$g\ X_S\ (gX_H)^{-1}\ d^{-1}$	Maximal growth rate on substrate
q_{fe}	3.00	$g\ X_S\ (gX_H)^{-1}\ d^{-1}$	Maximal fermentation rate
n_{NO3}	0.80		Reduction factor for denitrification
b_H	0.40	d^{-1}	Lysis rate constant
K_{O2}	0.20	$g\ O_2/m^3$	Saturation/inhibition coefficient for oxygen
K_F	4.00	$g\ COD\ m^{-3}$	Saturation coefficient for growth on SF
K_{fe}	4.00	$g\ COD\ m^{-3}$	Saturation coefficient for fermentation on SF
K_A	4.00	$g\ COD\ m^{-3}$	Saturation coefficient for acetate
K_{NO3}	0.50	$g\ N\ m^{-3}$	Saturation/inhibition coefficient for nitrate
K_{NH4}	0.05	$g\ N\ m^{-3}$	Saturation coefficient for SNH4 as nutrient
K_P	0.01	$g\ P\ m^{-3}$	Saturation coefficient for SPO4 as nutrient
K_{ALK}	0.10	$mole\ HCO^{3-}\ m^{-3}$	Saturation coefficient for alkalinity
Phosphorus-accumulating organisms: X_{PAO}			
q_{PHA}	3.00	$(g\ X_{PHA}(g\ X_{PAO})^{-1}\ d^{-1}$	Rate constant for storage of XPHA
q_{PP}	1.50	$(g\ X_{PHA}(g\ X_{PAO})^{-1}\ d^{-1}$	Rate constant for storage of XPP
u_{PAO}	1.00	d^{-1}	Maximum growth rate of XPAO
n_{NO3}	0.60		Reduction factor under anoxic conditions
b_{PAO}	0.20	d^{-1}	Rate for lysis of XPAO
b_{PP}	0.20	d^{-1}	Rate for lysis of XPP
b_{PHA}	0.20	d^{-1}	Rate for lysis of XPHA
K_{O2}	0.20	$g\ O_2\ m^{-3}$	Saturation coefficient for oxygen
K_{NO3}	0.50	$g\ N\ m^{-3}$	Saturation coefficient for nitrate
K_A	4.00	$g\ COD\ m^{-3}$	Saturation coefficient for acetate
K_{NH4}	0.05	$g\ N\ m^{-3}$	Saturation coefficient for ammonium
K_P	0.20	$g\ P\ m^{-3}$	Saturation coefficient for phosphate for XPP formation
K_{PO4}	0.01	$g\ P\ m^{-3}$	Saturation coefficient for phosphate for growth
K_{ALK}	0.10	$mole\ HCO^{3-}\ m^{-3}$	Saturation coefficient for alkalinity
K_{PP}	0.01	$g\ X_{PP}(g\ X_{PAO})^{-1}$	Saturation coefficient for polyphosphate
K_{MAX}	0.34	$g\ X_{PP}(g\ X_{PAO})\text{-}1$	Maximum ratio of XPP/XPAO
K_{IPP}	0.02	$g\ X_{PP}(g\ X_{PAO})\text{-}1$	Inhibition coefficient for polyphosphate storage
K_{PHA}	0.01	$g\ X_{PHA}(g\ X_{PAO})\text{-}1$	Saturation coefficient for PHA
Nitrifying organisms (autotrophic organisms): X_A			
u_{AUT}	1.00	d^{-1}	Maximal growth rate of autotrophic biomass
b_{AUT}	0.15	d^{-1}	Decay rate if autotrophic biomass
K_{O2}	0.50	$g\ O_2\ m^{-3}$	Saturation/inhibition coefficient for oxygen
K_{NH4}	1.00	$g\ N\ m^{-3}$	Saturation coefficient for SNH4
K_{ALK}	0.50	$mole\ HCO^{3-}\ m^{-3}$	Saturation coefficient for alkalinity
K_P	0.01	$g\ P\ m^{-3}$	Saturation coefficient for SPO4
Chemical phosphorus removal			
k_{PRE}	1.00	$m^3\ (gFe(OH)_3)^{-1}\ d^{-1}$	Rate constant for P precipitation
k_{RED}	0.60	d^{-1}	Rate constant for redissolution
K_{ALK}	0.50	$mole\ HCO^{3-}\ m^{-3}$	Saturation coefficient for alkalinity

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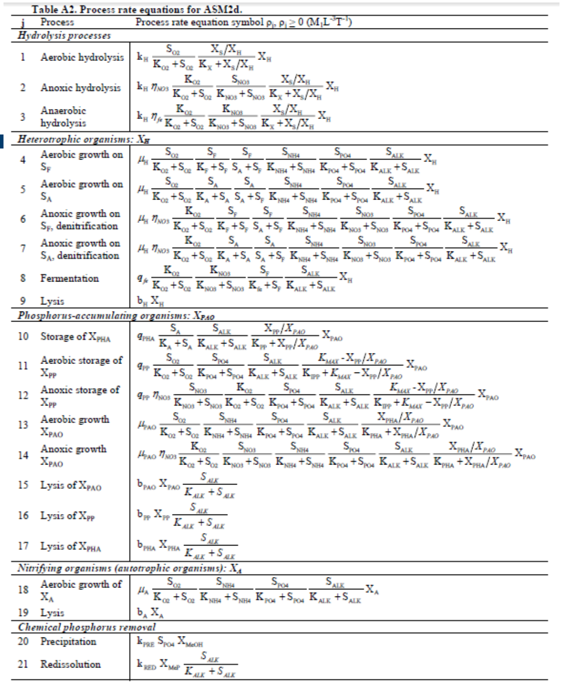


Table A2. Process rate equations for ASM2d.

j	Process	Process rate equation symbol ρ_j, $\rho_j \geq 0$ $(M_iL^{-3}T^{-1})$
Hydrolysis processes		
1	Aerobic hydrolysis	$k_H \frac{S_{O2}}{K_{O2}+S_{O2}} \frac{X_S/X_H}{K_X+X_S/X_H} X_H$
2	Anoxic hydrolysis	$k_H\ \eta_{NO3} \frac{K_{O2}}{K_{O2}+S_{O2}} \frac{S_{NO3}}{K_{NO3}+S_{NO3}} \frac{X_S/X_H}{K_X+X_S/X_H} X_H$
3	Anaerobic hydrolysis	$k_H\ \eta_{fe} \frac{K_{O2}}{K_{O2}+S_{O2}} \frac{K_{NO3}}{K_{NO3}+S_{NO3}} \frac{X_S/X_H}{K_X+X_S/X_H} X_H$
Heterotrophic organisms: X_H		
4	Aerobic growth on S_F	$\mu_H \frac{S_{O2}}{K_{O2}+S_{O2}} \frac{S_F}{K_F+S_F} \frac{S_F}{S_A+S_F} \frac{S_{NH4}}{K_{NH4}+S_{NH4}} \frac{S_{PO4}}{K_{PO4}+S_{PO4}} \frac{S_{ALK}}{K_{ALK}+S_{ALK}} X_H$
5	Aerobic growth on S_A	$\mu_H \frac{S_{O2}}{K_{O2}+S_{O2}} \frac{S_A}{K_A+S_A} \frac{S_A}{S_A+S_F} \frac{S_{NH4}}{K_{NH4}+S_{NH4}} \frac{S_{PO4}}{K_{PO4}+S_{PO4}} \frac{S_{ALK}}{K_{ALK}+S_{ALK}} X_H$
6	Anoxic growth on S_F, denitrification	$\mu_H\ \eta_{NO3} \frac{K_{O2}}{K_{O2}+S_{O2}} \frac{S_F}{K_F+S_F} \frac{S_F}{S_A+S_F} \frac{S_{NH4}}{K_{NH4}+S_{NH4}} \frac{S_{NO3}}{K_{NO3}+S_{NO3}} \frac{S_{PO4}}{K_{PO4}+S_{PO4}} \frac{S_{ALK}}{K_{ALK}+S_{ALK}} X_H$
7	Anoxic growth on S_A, denitrification	$\mu_H\ \eta_{NO3} \frac{K_{O2}}{K_{O2}+S_{O2}} \frac{S_A}{K_A+S_A} \frac{S_A}{S_A+S_F} \frac{S_{NH4}}{K_{NH4}+S_{NH4}} \frac{S_{NO3}}{K_{NO3}+S_{NO3}} \frac{S_{PO4}}{K_{PO4}+S_{PO4}} \frac{S_{ALK}}{K_{ALK}+S_{ALK}} X_H$
8	Fermentation	$q_{fe} \frac{K_{O2}}{K_{O2}+S_{O2}} \frac{K_{NO3}}{K_{NO3}+S_{NO3}} \frac{S_F}{K_{fe}+S_F} \frac{S_{ALK}}{K_{ALK}+S_{ALK}} X_H$
9	Lysis	$b_H\ X_H$
Phosphorus-accumulating organisms: X_{PAO}		
10	Storage of X_{PHA}	$q_{PHA} \frac{S_A}{K_A+S_A} \frac{S_{ALK}}{K_{ALK}+S_{ALK}} \frac{X_{PP}/X_{PAO}}{K_{PP}+X_{PP}/X_{PAO}} X_{PAO}$
11	Aerobic storage of X_{PP}	$q_{PP} \frac{S_{O2}}{K_{O2}+S_{O2}} \frac{S_{PO4}}{K_{PO4}+S_{PO4}} \frac{S_{ALK}}{K_{ALK}+S_{ALK}} \frac{K_{MAX}-X_{PP}/X_{PAO}}{K_{IPP}+K_{MAX}-X_{PP}/X_{PAO}} X_{PAO}$
12	Anoxic storage of X_{PP}	$q_{PP}\ \eta_{NO3} \frac{S_{NO3}}{K_{NO3}+S_{NO3}} \frac{K_{O2}}{K_{O2}+S_{O2}} \frac{S_{PO4}}{K_{PO4}+S_{PO4}} \frac{S_{ALK}}{K_{ALK}+S_{ALK}} \frac{K_{MAX}-X_{PP}/X_{PAO}}{K_{IPP}+K_{MAX}-X_{PP}/X_{PAO}} X_{PAO}$
13	Aerobic growth X_{PAO}	$\mu_{PAO} \frac{S_{O2}}{K_{O2}+S_{O2}} \frac{S_{NH4}}{K_{NH4}+S_{NH4}} \frac{S_{PO4}}{K_{PO4}+S_{PO4}} \frac{S_{ALK}}{K_{ALK}+S_{ALK}} \frac{X_{PHA}/X_{PAO}}{K_{PHA}+X_{PHA}/X_{PAO}} X_{PAO}$
14	Anoxic growth X_{PAO}	$\mu_{PAO}\ \eta_{NO3} \frac{K_{O2}}{K_{O2}+S_{O2}} \frac{S_{NO3}}{K_{NO3}+S_{NO3}} \frac{S_{NH4}}{K_{NH4}+S_{NH4}} \frac{S_{PO4}}{K_{PO4}+S_{PO4}} \frac{S_{ALK}}{K_{ALK}+S_{ALK}} \frac{X_{PHA}/X_{PAO}}{K_{PHA}+X_{PHA}/X_{PAO}} X_{PAO}$
15	Lysis of X_{PAO}	$b_{PAO}\ X_{PAO} \frac{S_{ALK}}{K_{ALK}+S_{ALK}}$
16	Lysis of X_{PP}	$b_{PP}\ X_{PP} \frac{S_{ALK}}{K_{ALK}+S_{ALK}}$
17	Lysis of X_{PHA}	$b_{PHA}\ X_{PHA} \frac{S_{ALK}}{K_{ALK}+S_{ALK}}$
Nitrifying organisms (autotrophic organisms): X_A		
18	Aerobic growth of X_A	$\mu_A \frac{S_{O2}}{K_{O2}+S_{O2}} \frac{S_{NH4}}{K_{NH4}+S_{NH4}} \frac{S_{PO4}}{K_{PO4}+S_{PO4}} \frac{S_{ALK}}{K_{ALK}+S_{ALK}} X_A$
19	Lysis	$b_A\ X_A$
Chemical phosphorus removal		
20	Precipitation	$k_{PRE}\ S_{PO4}\ X_{MeOH}$
21	Redissolution	$k_{RED}\ X_{MeP} \frac{S_{ALK}}{K_{ALK}+S_{ALK}}$

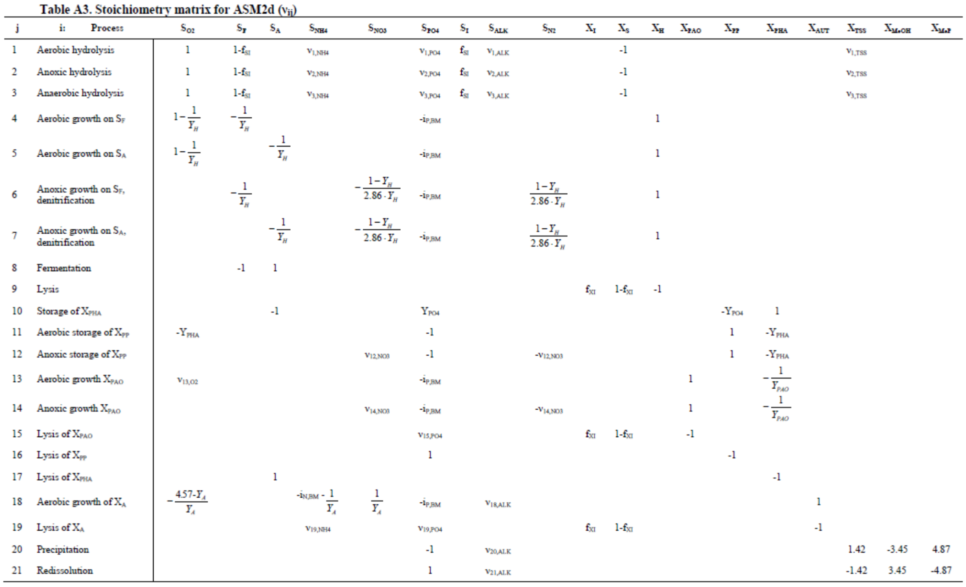
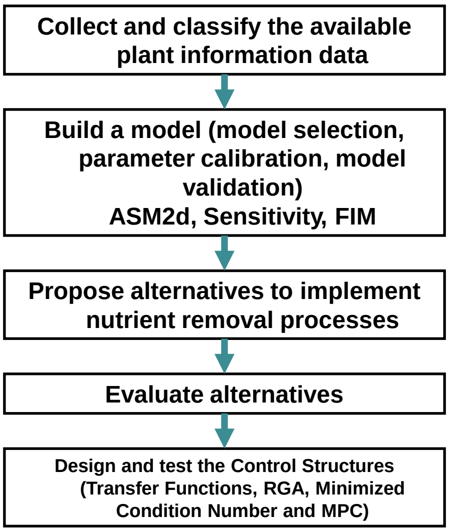


Table A3. Stoichiometry matrix for ASM2d (v_{ij})

j	i: Process	S_{O2}	S_F	S_A	S_{NH4}	S_{NO3}	S_{PO4}	S_I	S_{ALK}	S_{N2}	X_I	X_S	X_H	X_{PAO}	X_{PP}	X_{PHA}	X_{AUT}	X_{TSS}	X_{MeOH}	X_{MeP}
1	Aerobic hydrolysis	1	$1-f_{SI}$		$v_{1,NH4}$		$v_{1,PO4}$	f_{SI}	$v_{1,ALK}$			-1						$v_{1,TSS}$		
2	Anoxic hydrolysis	1	$1-f_{SI}$		$v_{2,NH4}$		$v_{2,PO4}$	f_{SI}	$v_{2,ALK}$			-1						$v_{2,TSS}$		
3	Anaerobic hydrolysis	1	$1-f_{SI}$		$v_{3,NH4}$		$v_{3,PO4}$	f_{SI}	$v_{3,ALK}$			-1						$v_{3,TSS}$		
4	Aerobic growth on S_F	$1-\frac{1}{Y_H}$	$-\frac{1}{Y_H}$				$-i_{P,BM}$						1							
5	Aerobic growth on S_A	$1-\frac{1}{Y_H}$		$-\frac{1}{Y_H}$			$-i_{P,BM}$						1							
6	Anoxic growth on S_F, denitrification		$-\frac{1}{Y_H}$			$-\frac{1-Y_H}{2.86 \cdot Y_H}$	$-i_{P,BM}$			$\frac{1-Y_H}{2.86 \cdot Y_H}$			1							
7	Anoxic growth on S_A, denitrification			$-\frac{1}{Y_H}$		$-\frac{1-Y_H}{2.86 \cdot Y_H}$	$-i_{P,BM}$			$\frac{1-Y_H}{2.86 \cdot Y_H}$			1							
8	Fermentation		-1	1																
9	Lysis										f_{XI}	$1-f_{XI}$	-1							
10	Storage of X_{PHA}			-1			Y_{PO4}								$-Y_{PO4}$	1				
11	Aerobic storage of X_{PP}	$-Y_{PHA}$					-1								1	$-Y_{PHA}$				
12	Anoxic storage of X_{PP}					$v_{12,NO3}$	-1			$-v_{12,NO3}$					1	$-Y_{PHA}$				
13	Aerobic growth X_{PAO}	$v_{13,O2}$					$-i_{P,BM}$							1		$-\frac{1}{Y_{PAO}}$				
14	Anoxic growth X_{PAO}					$v_{14,NO3}$	$-i_{P,BM}$			$-v_{14,NO3}$				1		$-\frac{1}{Y_{PAO}}$				
15	Lysis of X_{PAO}						$v_{15,PO4}$				f_{XI}	$1-f_{XI}$		-1						
16	Lysis of X_{PP}						1								-1					
17	Lysis of X_{PHA}			1												-1				
18	Aerobic growth of X_A	$-\frac{4.57-Y_A}{Y_A}$			$-i_{N,BM}-\frac{1}{Y_A}$	$\frac{1}{Y_A}$	$-i_{P,BM}$		$v_{18,ALK}$								1			
19	Lysis of X_A				$v_{19,NH4}$		$v_{19,PO4}$				f_{XI}	$1-f_{XI}$					-1			
20	Precipitation						-1		$v_{20,ALK}$									1.42	-3.45	4.87
21	Redissolution						1		$v_{21,ALK}$									-1.42	3.45	-4.87

WWTP modelling



Collect and classify the available plant information data

Build a model (model selection, parameter calibration, model validation)
ASM2d, Sensitivity, FIM

Propose alternatives to implement nutrient removal processes

Evaluate alternatives

Design and test the Control Structures (Transfer Functions, RGA, Minimized Condition Number and MPC)

WWTP modelling

ASM2d calibration

- **Influent characterisation**

Plant data:

- COD
- BOD5
- TKN
- NH_4
- NO_3
- PO_4
- VSS
- TSS

→

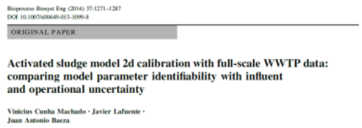
ASM2d state variables:

Symbol	Description	Symbol	Description
S_{O2}	Dissolved oxygen concentration, [g O_2 m^{-3}]	X_S	Slowly biodegradable substrates, [g COD m^{-3}]
S_F	Readily biodegradable soluble organic substrate, [g COD m^{-3}]	X_H	Heterotrophic organisms, [g COD m^{-3}]
S_A	Fermentation products VFA, [g COD m^{-3}]	X_{PAO}	Phosphorus accumulating organisms, [g COD m^{-3}]
S_I	Inert soluble organic material,[g COD m^{-3}]	X_{PP}	Polyphosphate, [g P m^{-3}]
S_{NH4}	Ammonium plus ammonia nitrogen, [g N m^{-3}]	X_{PHA}	Cell internal storage product of PAO, [g COD m^{-3}]
S_{N2}	Gaseous nitrogen, [g N m^{-3}]	X_{AUT}	Nitrifying organisms, [g COD m^{-3}]
S_{NO3}	Nitrate plus nitrite nitrogen, [g N m^{-3}]	X_{TSS}	Total suspended solids, TSS, [g TSS m^{-3}]
S_{PO4}	Inorganic soluble phosphorus, [g P m^{-3}]	X_{MeOH}	Metal-hydroxides, involved with chemical removal of phosphorus, [g TSS m^{-3}]
S_{ALK}	Alkalinity of the wastewater, [mol HCO_3^- m^{-3}]	X_{MeP}	Metal phosphate, [g TSS m^{-3}]
X_I	Inert particulate organic material, [g COD m^{-3}]		

WWTP modelling

ASM2d calibration

- **Available plant information**



Bioprocess Biosyst Eng (2014) 37:1271–1287
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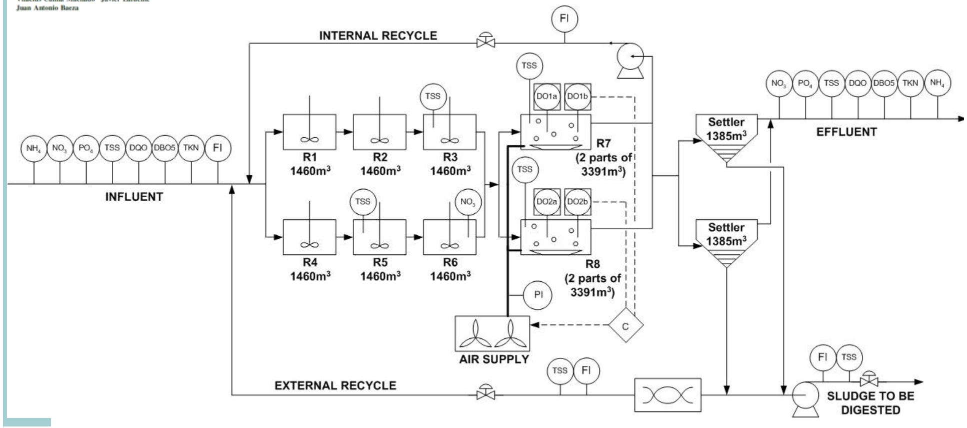
ORIGINAL PAPER

Activated sludge model 2d calibration with full-scale WWTP data: comparing model parameter identifiability with influent and operational uncertainty

Vinicius Cunha Machado · Javier Lafuente · Juan Antonio Baeza



WWTP modelling

ASM2d calibration

- **Selection of parameters to fit**

Sensitivity analysis/ Identifiability

$$S_{ij} = \frac{\theta_j}{y_i}\frac{dy_i}{d\theta_j}$$

$$OS_j = \left|S_{j,PO_4}\right| + \left|S_{j,NH_4}\right| + \left|S_{j,NO_3}\right| + \left|S_{j,XTSS}\right| + \left|S_{j,TKN}\right|$$

$$FIM = \sum_{k=1}^{N} Y_\theta(k) \cdot Q_k^{-1} \cdot Y_\theta^T(k)$$

Kinetic / Stoichiometric Group (K group)

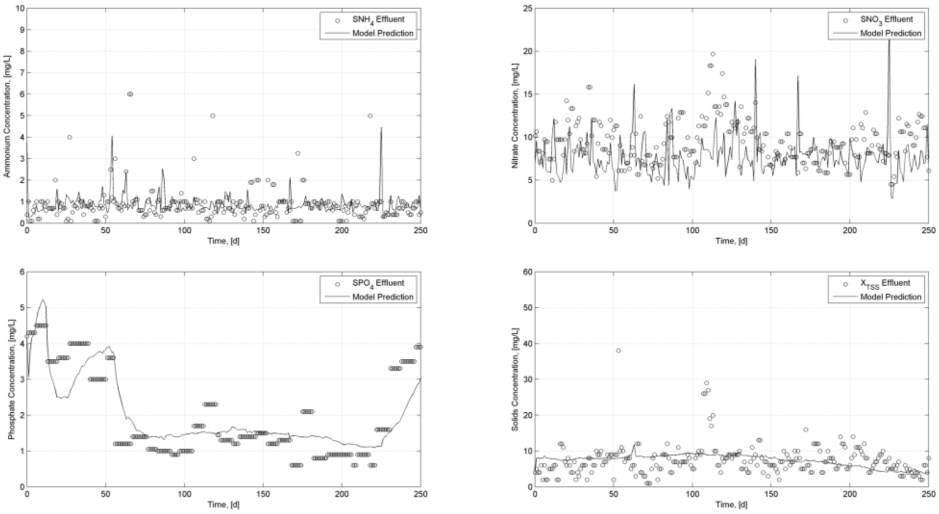
Order	Parameter	Short Description	Related biomass or process	Sensitivity
1	Y_H	Yield coefficient for X_H.	Heterotrophic	756
2	μ_A	Maximum growth rate of X_A	Autotrophic	678
3	b_A	Rate for lysis of X_A	Autotrophic	634
4	$K_{NH4,A}$	Saturation coefficient of substrate NH_4^+ for nitrification on S_{NH4}	Autotrophic	412
5	K_{PRE}	Precipitation constant	Chemical phosphate precipitation	150
6	$K_{O2,A}$	Saturation coefficient of O_2 for nitrification on S_{NH4}	Autotrophic	149
7	K_{RED}	Solubilisation constant	Chemical phosphate precipitation	148
8	b_H	Rate for lysis of X_H	Heterotrophic	97
9	$K_{ALK,A}$	Saturation coefficient of alkalinity for nitrification on S_{NH4}	Autotrophic	73
10	$\eta_{NO3,D}$	Reduction factor for denitrification	Heterotrophic	51

WWTP modelling

$$CCF = \sum_{i=1}^{5} w_i \sqrt{\cdot \sum_{j=1}^{n} \left(y_{exp\ i,j} - y_{model\ i,j}\right)^2}$$

ASM2d calibration

- **Model fit.** **Minimisation of a calibration cost function**



WWTP modelling

After a proper process of **model calibration** and **validation**, we can be confident that we have a model able to provide a **good description of** the simulated variables in **that particular WWTP**

However, we need to calculate different **performance indicators** as a tool for comparison of the behaviour of the WWTP under several **operating conditions** or **control strategies**

Performance Indicators

WWTP performance with different control strategies is evaluated following typical benchmarking efficiency criteria

- Operational Costs: Aeration, Pumping, Sludge Treatment, Effluent Fines
- Effluent Quality Index: Ammonium, Total Nitrogen, Phosphorus
- Time above limits
- Mean effluent values

But other non-typical criteria have been also considered

- Microbiological Risks of bulking and foaming
- Greenhouse Gas Emissions

Performance Indicators

Operating Cost

$$OC[€\ d^{-1}] = \gamma_E (AE + PE) + \gamma_{SP} SP + EF$$

Aeration Energy

$$AE\,[kWh\ d^{-1}] = 24 \left[\sum_{i=5}^{7} 0.0007 (k_L a_i)^2 + 0.3267\ k_L a_i \right]$$

Pumping Energy

$$PE\,[kWh\ d^{-1}] = P_F (Q_{RINT} + Q_{RAS} + Q_W)$$

Sludge Production

$$SP[kg\ d^{-1}] = X_{TSS}^{Q_W} \cdot Q_W$$

Effluent Fines

$$EF(€\, d^{-1}) = \sum_{j=NH_4,TN,PO_4} Q_{EFF} \Delta\alpha_j C_j^{EFF} + Q_{EFF} [\beta_{0,j} + (C_j^{EFF} - C_{L,j})(\Delta\beta_j - \Delta\alpha_j)] Heaviside (C_j^{EFF} - C_{L,j})$$

Typical Characteristics

These criteria are used in combination to give a single cost function in monetary units or they are used as a multiobjective function.

Typical benchmarking influents are used: dry, rain and storm.

The classical 14 days evaluation period has been widely reported.

Complete evaluation periods include 300 days of simulation to reach steady state with constant influent data, then 609 days of long term dynamic influent. Only the last 364 days are used for evaluation.

The typical anaerobic/anoxic/aerobic configuration (A^2/O) including N/D and EBPR is the more studied WWTP. Other configurations also evaluated: UCT, Carrousel and Johannesburg.

ASM2d is the model most widely used for evaluation.

A2/O Configuration

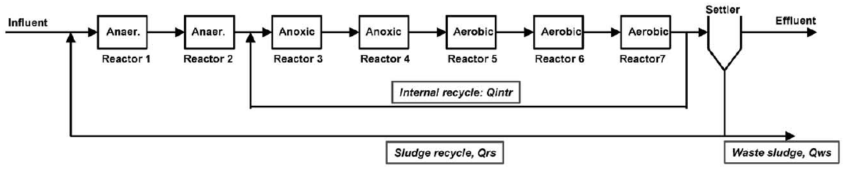


Fig. 1. Lay-out of the benchmark plant for evaluation of control strategies on combined N and P removal processes.


PERGAMON

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Control Engineering Practice 12 (2004) 357–373

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Benchmarking combined biological phosphorus and nitrogen removal wastewater treatment processes

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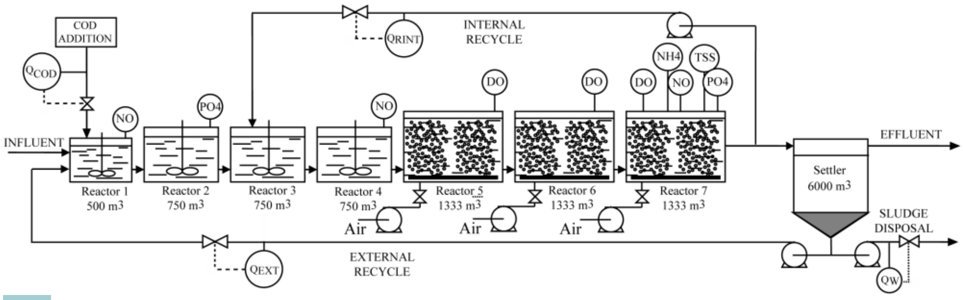
Accepted 26 March 2003

A2/O Configuration

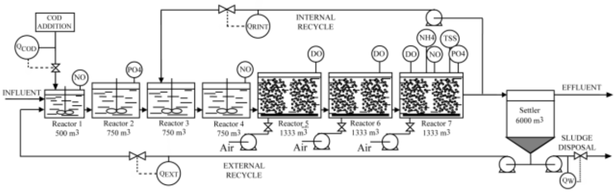


A^2/O WWTP for simultaneous C/N/P removal

A2/O Configuration

Measurement Points and Monitored Variables

- DO in the aerobic reactors (R5, R6 and R7)
- PO_4^{3-} at the end of the anaerobic zone (R2) and at the end of the aerobic zone (R7)
- NO_3^- at the end of the anoxic zone (R4) and at the end of the aerobic zone (R7)
- NH_4^+ at the end of the aerobic zone (R7) and in the influent
- Influent flow-rate
- Total Suspended Solids



Manipulated Variables

- Aeration in R5, R6 and R7: k_La_5, k_La_6 and k_La_7
- DO setpoint in R5, R6 and R7
- External carbon source addition: Q_{COD}
- Internal recycle flow-rate: Q_{RINT}
- External recycle flow-rate: Q_{REXT}
- Purge flow-rate: Q_W

Typical Control Loops

Single Input Single Output (SISO) Controllers

- PI
- PID
- Slave PI - Cascade

Multiple Input Multiple Output (MIMO) Controllers

- MPC

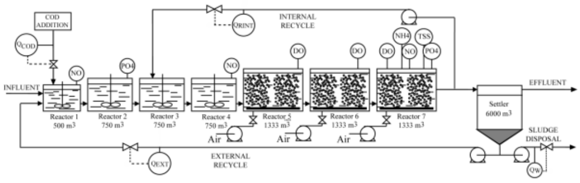
Supervisory Control

- Cost Controller
- Expert Systems: KBES, Decision Trees…

Control Structures

Typical Control Structures based on Expertise with effect on P-removal

Controlled Variable	Manipulated Variable	Controller
DO R5, R6, R7	k_La_5, k_La_6, k_La_7	PI
NO_3^- in R4	Q_{RINT}	PI
NH_4^+ in R7	DO_{SP} in R5, R6, R7	Cascade - PI
TSS in R7	Q_W	PI
PO_4^{3-} in R7	Q_{COD}	PID
NH_4^+ in R7	DO_{SP} in R5, R6, R7	Feedforward Q_{IN}, $NH_4^+{}_{IN}$



Control Structures

The performance of these Control Structures can be optimised

- Tuning of controller parameters
- Optimization of setpoints

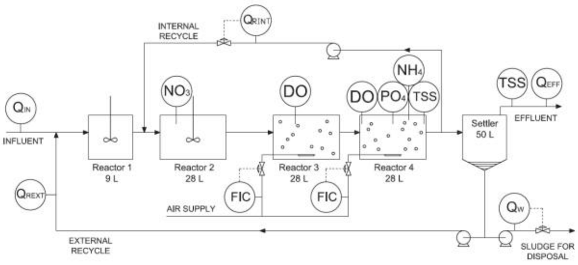


Fig. 1. Scheme of the A^2/O simulated plant for simultaneous C/N/P remova

Controlled Variable	Manipulated Variable	Controller
DO R3, R4	k_La_3, k_La_4	PI
NO_3^- in R2	Q_{RINT}	PI
NH_4^+ in R4	DO_{SP} in R3, R4	Cascade - PI
TSS in R4	Q_W	PI


Environmental Modelling & Software 26 (2011) 492–497

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Environmental Modelling & Software

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ELSEVIER

Improving the performance of a WWTP control system by model-based setpoint optimisation

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Control Structures

Optimization of setpoints allows to obtain the better performance of a CS

Minimization of a Cost Function where all the criteria considered are converted to monetary units.

ANALYSED SCENARIOS

- **Open Loop (OL):** TSS control loop in R4. Aeration constant in R3 and R4. $Q_{RINT}/Q_I = 3$, $Q_{REXT}/Q_I = 1$.
- **DO control (DOC):** DO control was activated with a setpoint of 4 mg DO L^{-1} in R3 and R4.
- **Maximum performance for nutrient removal (MPR):** Ammonia setpoint was 0 mg L^{-1} and nitrate setpoint was optimised to minimise nitrate in the effluent.
- **Ammonium and nitrate fixed optimum setpoints (A&N-FOS):** Fixed optimum ammonium and nitrate setpoints.
- **Ammonium and nitrate daily variable optimum setpoints (A&N-DVOS):** Setpoints daily optimised according to the influent flow pattern of the plant.
- **Ammonium and nitrate weekly variable optimum setpoints (A&N-WVOS):** Two different sets of setpoints are optimised, one for weekend and one for the weekdays.
- **Ammonium and nitrate hourly variable optimum setpoints (A&N-HVOS):** Setpoints are hourly optimised according to the influent flow pattern of the plant.

Control Structures

Conclusions of the optimisation study

- Model-based optimisation of the setpoints of WWTP control loops provides low effluent discharges with minimal OC (decrease of OC up to 45% and a reduction up to 72% of the time above discharge limits) when compared to the open loop scenario.
- The implementation of a control strategy with the model-based setpoint optimisation of ammonium and nitrate concentration improves not only the removal of these compounds, but also enhances EBPR.
- The implementation of different sets of setpoints for weekdays, weekends and storm or rain episodes (A&N-WVOS) was the most efficient control strategy considering the OC and the time above limits.
- The hourly retuning of the control setpoints was not an efficient strategy because it increased the total costs after the whole period of 14 days. More complex is not always better!

Control Structures

Optimisation of a multi-criteria function

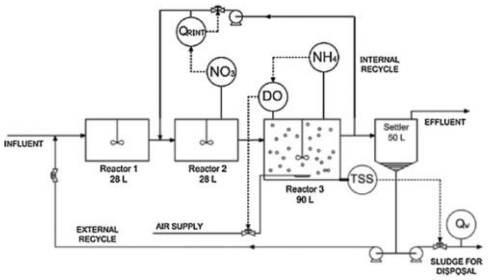
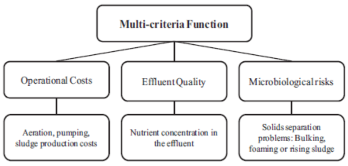


Fig. 1. Schematic representation of the plant with an A^2/O configuration and the implemented control loops. Dashed lines represent the manipulated variables of the control loops.



Multi-criteria Function

- Operational Costs
  - Aeration, pumping, sludge production costs
- Effluent Quality
  - Nutrient concentration in the effluent
- Microbiological risks
  - Solids separation problems: Bulking, foaming or rising sludge

Fig. 2. Three dimensional multi-criteria function.

Chemical Engineering Journal 188 (2012) 23–29

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Multi-criteria selection of optimum WWTP control setpoints based on microbiology-related failures, effluent quality and operating costs

J. Guerrero[a,1], A. Guisasola[a,*], J. Comas[b,2], I. Rodríguez-Roda[b,c,3], J.A. Baeza[a,4]

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Control Structures

Optimisation of a multivariable function

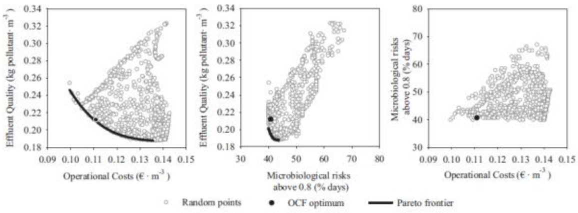

Fig. 5. Results of the 1500 random set of setpoints analysed for A&N-FS control strategy using the MCF.

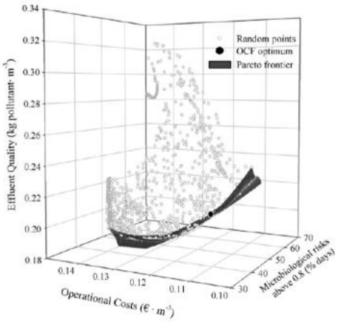

Fig. 6. Three-dimensional representation of the A&N-FS control strategy behaviour in terms of operational costs, effluent quality and microbiological risks for 1500 random set of setpoints.

Chemical Engineering Journal 188 (2012) 23–29

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Control Structures

Conclusions of the multi-criteria study

- Multi-criteria optimisation provides a set of optimal operation setpoints approximated by a Pareto surface. The optimised setpoint within this surface can be selected by the requirements that are established for each WWTP in terms of the three criteria.
- These requirements can be translated into monetary weights as was done with OCF. OCF optimisation results in an optimised scenario located on Pareto surface.
- The approaches of single OCF or multi-criteria are complementary. The multi-criteria function enabled a more extensive evaluation of different alternatives where none of the criterion is conditional to the other. Once the weights are selected according to the WWTP requirements, the OCF optimisation could be used to adapt the plant operation to the influent variations.

Control Structures

Selection of CS based on classical control tools

Plant Modelling:

Step 1: ASM2d + Parameter Calibration

(Non-Linear Model)

Step 2: Linearization of the model identified in Step 1 at the most common operating point, using system identification techniques

(Transfer Function Matrix – FOPTD linear models)

Control Structures

Selection of CS based on classical control tools

Relative Gain Array (RGA)

Tool for selecting decentralized control structures

$$RGA(\omega) = G(\omega)\cdot\left(G^{-1}(\omega)\right)^{T}$$

Information 1: Best pairing

Information 2: Best set of variables

Control Matrix		Handle Variables				
		Manipulated Variables (MV)				Disturbance (DV)
		MV1	MV2	MV3	MV4	DV1
Controlled Variables (CV)	CV1	1.00	0.00	0.00	0.00	--
	CV2	0.00	1.00	0.00	0.00	--
	CV3	0.00	0.00	1.00	0.00	--
	CV4	0.00	0.00	0.00	1.00	--

Control Structures

Application of RGA to P-removal with EBPR

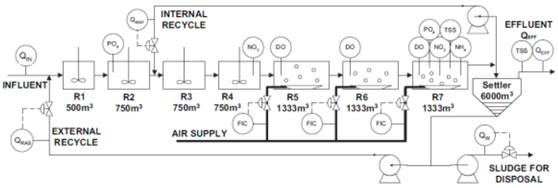
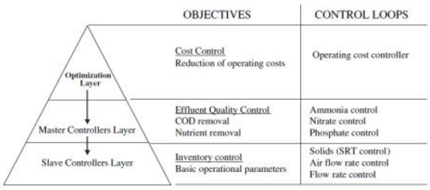


Fig. 1 – Scheme of the A^2/O wastewater treatment line for organic matter, N and P removal.



OBJECTIVES	CONTROL LOOPS
Cost Control Reduction of operating costs	Operating cost controller
Effluent Quality Control COD removal Nutrient removal	Ammonia control Nitrate control Phosphate control
Inventory control Basic operational parameters	Solids (SRT control) Air flow rate control Flow rate control

Fig. 3 – Control hierarchy implemented in the A^2/O WWTP.

WATER RESEARCH 43 (2009) 5129–5141

Available at www.sciencedirect.com
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Cost and effluent quality controllers design based on the relative gain array for a nutrient removal WWTP

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Control Structures

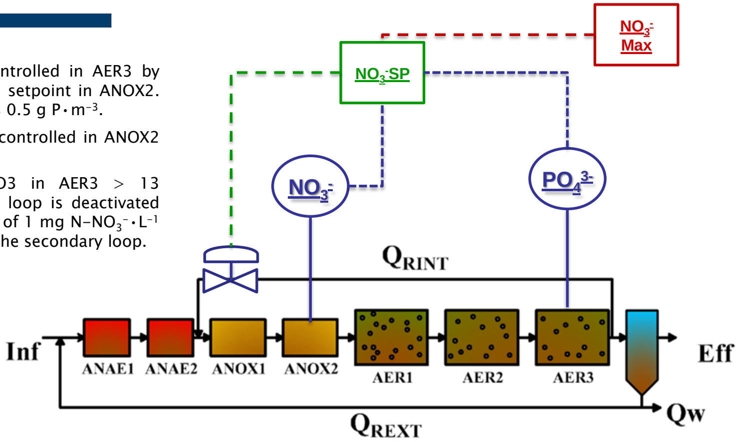
Application of RGA to P-removal with EBPR

- Process control theory tools, such as RGA, allow the systematic design of control structures that improve WWTP performance.
- RGA was used for building decentralised effluent quality controllers. The best control structure selected was a decentralized control structure with NH4R7, NO3R4 and PO4R2 as controlled variables. This structure had the lowest degree of interaction among input and output variables. This allows saving energy of manipulated variables since internal disturbances are minimized.
- The selected control structure could save up to 42,000 Euros/year in comparison to the plant operating with DO control.
- The benefits increased by including the cost controller. The introduction of this controller reduces the costs approaching to the minimum cost obtained with optimised setpoints.

New Control Strategies In The Literature

Cascade + Override Phosphorus Control Strategy (COPCS)

- Primary loop. PO4 controlled in AER3 by manipulating the NO3 setpoint in ANOX2. P setpoint in AER3 was 0.5 g P·m^{-3}.
- Secondary loop. NO3 controlled in ANOX2 by manipulating Q_{RINT}
- Override loop. If NO3 in AER3 > 13 mgN·L^{-1}, the primary loop is deactivated and a default setpoint of 1 mg N-NO_3^-·L^{-1} for ANOX2 is fixed in the secondary loop.

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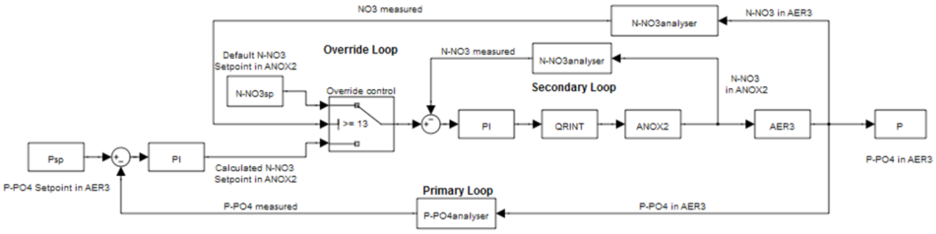
A novel control strategy for efficient biological phosphorus removal with carbon-limited wastewaters

Javier Guerrero, Albert Guisasola and Juan A. Baeza

New Control Strategies In The Literature

Cascade + Override Phosphorus Control Strategy (COPCS)

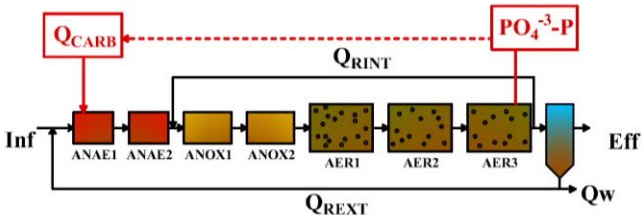


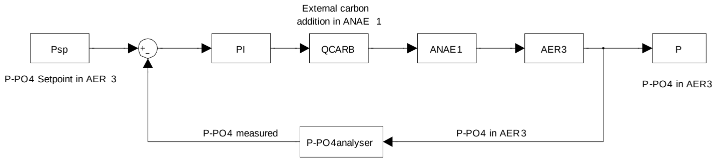
In the case of low carbon content wastewater, this strategy allows to divert the COD to EBPR.
Only in case TN limits are not accomplished the primary control loop is deactivated to improve denitrification.

New Control Strategies In The Literature

Cascade + Override Phosphorus Control Strategy (COPCS)

Conventional alternative: Q_{CARB}: External carbon source addition as manipulated variable

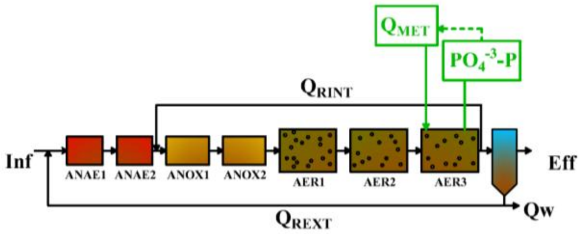


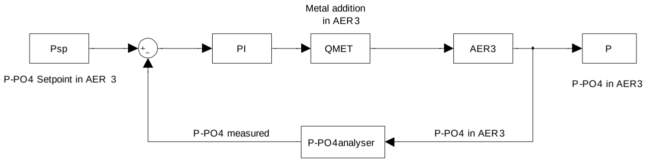

External carbon
addition in ANAE 1
Psp
PI
QCARB
ANAE1
AER3
P
P-PO4 Setpoint in AER 3
P-PO4 in AER3
P-PO4 measured
P-PO4analyser
P-PO4 in AER3

New Control Strategies In The Literature

Cascade + Override Phosphorus Control Strategy (COPCS)

Conventional alternative: Q_{MET}: Metal addition as manipulated variable





Metal addition in AER3

Psp

+ -

PI

QMET

AER3

P

P-PO4 Setpoint in AER 3

P-PO4 in AER3

P-PO4 measured

P-PO4analyser

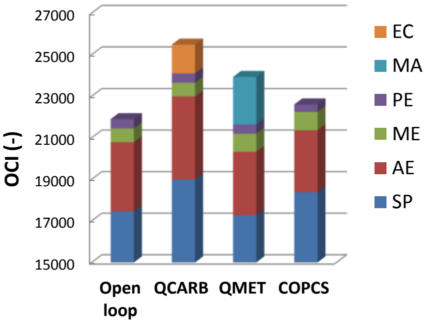
P-PO4 in AER3

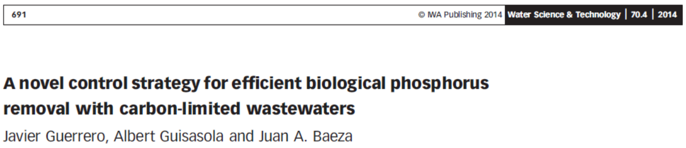
New Control Strategies In The Literature

Cascade + Override Phosphorus Control Strategy (COPCS)

Effluent quality and operating costs comparison

Effluent concentrations (g · m−3)	Open loop	Q_{CARB}	Q_{MET}	COPCS
$N\text{-}NH_4^+$	1.32	1.65	2.23	2.85
TN	7.63	7.14	7.77	9.13
$P\text{-}PO_4^{3-}$	2.49	0.34	0.31	0.61
TP	3.27	1.24	1.25	1.51





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A novel control strategy for efficient biological phosphorus removal with carbon-limited wastewaters

Javier Guerrero, Albert Guisasola and Juan A. Baeza

Link current models with the design of new control strategies

Conventional models used for designing P-removal control strategies are based on ASM2d

K.V. Gernaey, S.B. Jorgensen / Control Engineering Practice 12 (2004) 357–373

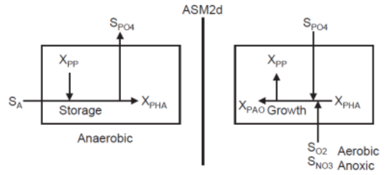

Fig. 2. Illustration of the basic principles behind the biological P removal process as included in the ASM2d model.

Although ASM2d provides a good description of EBPR processes at full-scale WWTP, it has important limitations that should be considered when developing new P-control strategies…

Link current models with the design of new control strategies

ASM2d limitations … and consequences in control design

- Nitrification is modelled as a one-step process. Two-step nitrification and denitrification is not considered.
  → strategies considering nitrite pathway can not be simulated. ASM2d extension is required. Nitrite-DPAO activity should be considered.
- N_2O production during nitrification or denitrification is not modelled.
  → GHG emission can not be estimated, ASM2d extension is required.
- PAO appear as a single type of population. However, there are PAO with different denitrification abilities (PAOI/PAOII), new PAO species (Tetrasphaera PAO) and also different GAO populations (Competibacter, DF1, DF2, DF3, DF4 …).
  → Model parameters for PAO can be calibrated for a given WWTP microbial community. However, the evolution of the sludge would require a periodic recalibration of these parameters (μ_{PAO}, Y_{PO4}, Y_{PHA}, Y_{PAO}, q_{PHA}, q_{PP} , η_{NO3}…)
- pH effect of processes is not modelled. Biological-induced precipitation is not described.

Link current models with the design of new control strategies

ASM2d limitations … and consequences in control design

- Preference for substrate is not included. PAO preferred carbon source is propionate.
  → More stable operation anaerobic/aerobic or anaerobic/anoxic has been reported. However, the same behaviour is predicted as only S_A is considered.

- Glycogen is not considered as a state variable.
  → Real process failures unpredicted by the model (lack of reducing power).

- Identifiability of model parameters. Correlation of parameters in experiments with low information content. Parameters should have their confidence interval estimated.
  → Unreliable model predictions. Which is the uncertainty of the predictions?

- Influent characterization is critical to obtain a good prediction.
  → Benchmarking tools provide a good starting point of influent to study control response, but the characterization of the influent of a real WWTP to the level required by ASM2d is not feasible in practice.

Link current models with the design of new control strategies

Modelling and equipment limitations … and consequences in control design

- Model predictions are not as exact as they may seem, important simplifications are included in the modelling exercise:
  - WWTP reactors are not perfectly mixed, they are not CSTR, there are gradients of concentration, short-circuiting, dead volume, imbalances in lines …
  - Analyser measurement is considered 100% representative of the reactor content. Sampling point is critical!
  - Settlers in real life are reactive. Some processes are occurring, but not at the rate of a CSTR. Settlers are not stirred, diffusion limitations are higher than in a CSTR.
  - DO control loops mainly rely on k_La oxygen transfer coefficients as manipulated variable. Modelling of oxygen transfer as a function of aeration flow should be improved.

- Some controllers are based on linear models.
  - Linear models are only valid near to the linearization point. Using them far from these points means extrapolation.

Link current models with the design of new control strategies

Modelling and equipment limitations … and consequences in control design

- Analysers precision is limited.
  - Several setpoints reported in the literature cannot be achieved in practice. A sensitivity analysis of optimised controllers setpoint should be performed.
- Manipulated variables have a limited range of operation.
  - Limits must be considered for all the equipment.
  - Anti wind-up controllers should be used.
- Optimization of controller setpoint provides better improvements than the perfect tuning of the controller.
- Sensors dynamics should be considered, but the WWTP dynamics is usually much slower.
- Only water line is usually modelled for control. Internal P inputs from reject water and other recycle streams should be also considered.

Acknowledgments

UAB
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Activated sludge: 100 *plus* 1 years
New trends and perspectives
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Thank you for your attention!

Grazie per la vostra attenzione!

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Control Structures

Application of Non-Square Relative Gain Array (NSRGA) to WWTP with EBPR

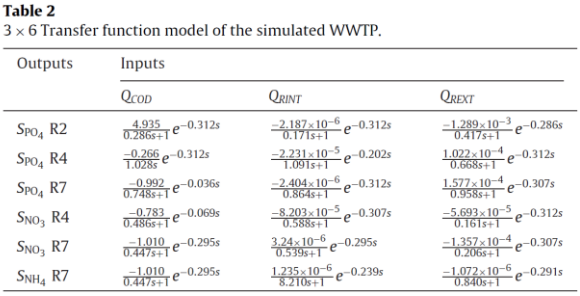
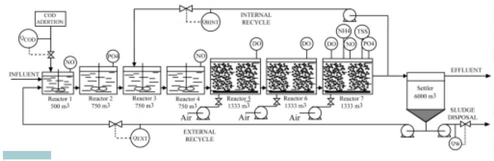
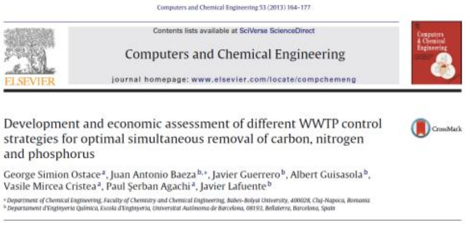


Table 2
3 × 6 Transfer function model of the simulated WWTP.

Outputs	Inputs		
	Q_{COD}	Q_{RINT}	Q_{REXT}
S_{PO_4} R2	$\frac{4.935}{0.286s+1}e^{-0.312s}$	$\frac{-2.187\times10^{-6}}{0.171s+1}e^{-0.312s}$	$\frac{-1.289\times10^{-3}}{0.417s+1}e^{-0.286s}$
S_{PO_4} R4	$\frac{-0.266}{1.028s}e^{-0.312s}$	$\frac{-2.231\times10^{-5}}{1.091s+1}e^{-0.202s}$	$\frac{1.022\times10^{-4}}{0.668s+1}e^{-0.312s}$
S_{PO_4} R7	$\frac{-0.992}{0.748s+1}e^{-0.036s}$	$\frac{-2.404\times10^{-6}}{0.864s+1}e^{-0.312s}$	$\frac{1.577\times10^{-4}}{0.958s+1}e^{-0.307s}$
S_{NO_3} R4	$\frac{-0.783}{0.486s+1}e^{-0.069s}$	$\frac{-8.203\times10^{-5}}{0.588s+1}e^{-0.307s}$	$\frac{-5.693\times10^{-5}}{0.161s+1}e^{-0.312s}$
S_{NO_3} R7	$\frac{-1.010}{0.447s+1}e^{-0.295s}$	$\frac{3.24\times10^{-6}}{0.539s+1}e^{-0.295s}$	$\frac{-1.357\times10^{-4}}{0.206s+1}e^{-0.307s}$
S_{NH_4} R7	$\frac{-1.010}{0.447s+1}e^{-0.295s}$	$\frac{1.235\times10^{-6}}{8.210s+1}e^{-0.239s}$	$\frac{-1.072\times10^{-6}}{0.840s+1}e^{-0.291s}$





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ELSEVIER

Development and economic assessment of different WWTP control strategies for optimal simultaneous removal of carbon, nitrogen and phosphorus

George Simion Ostace[a], Juan Antonio Baeza[b,*], Javier Guerrero[b], Albert Guisasola[b], Vasile Mircea Cristea[a], Paul Şerban Agachi[a], Javier Lafuente[b]

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Control Structures

Activated sludge: 100 *plus* 1 years
New trends and perspectives

Application of Non-Square Relative Gain Array (NSRGA) to WWTP with EBPR

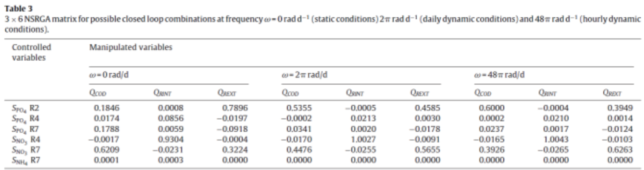


Table 3
3 × 6 NSRGA matrix for possible closed loop combinations at frequency $\omega = 0$ rad d^{-1} (static conditions) 2π rad d^{-1} (daily dynamic conditions) and 48π rad d^{-1} (hourly dynamic conditions).

Controlled variables	Manipulated variables								
	$\omega = 0$ rad/d			$\omega = 2\pi$ rad/d			$\omega = 48\pi$ rad/d		
	Q_{COD}	Q_{RINT}	Q_{REXT}	Q_{COD}	Q_{RINT}	Q_{REXT}	Q_{COD}	Q_{RINT}	Q_{REXT}
S_{PO_4} R2	0.1846	0.0008	0.7896	0.5355	−0.0005	0.4585	0.6000	−0.0004	0.3949
S_{PO_4} R4	0.0174	0.0856	−0.0197	−0.0002	0.0213	0.0030	0.0002	0.0210	0.0014
S_{PO_4} R7	0.1788	0.0059	−0.0918	0.0341	0.0020	−0.0178	0.0237	0.0017	−0.0124
S_{NO_3} R4	−0.0017	0.9304	−0.0004	−0.0170	1.0027	−0.0091	−0.0165	1.0043	−0.0103
S_{NO_3} R7	0.6209	−0.0231	0.3224	0.4476	−0.0255	0.5655	0.3926	−0.0265	0.6263
S_{NH_4} R7	0.0001	0.0003	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

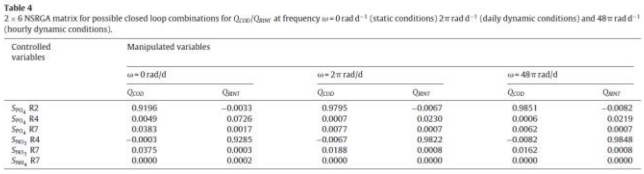


Table 4
2 × 6 NSRGA matrix for possible closed loop combinations for Q_{COD}/Q_{RINT} at frequency $\omega = 0$ rad d^{-1} (static conditions) 2π rad d^{-1} (daily dynamic conditions) and 48π rad d^{-1} (hourly dynamic conditions).

Controlled variables	Manipulated variables					
	$\omega = 0$ rad/d		$\omega = 2\pi$ rad/d		$\omega = 48\pi$ rad/d	
	Q_{COD}	Q_{RINT}	Q_{COD}	Q_{RINT}	Q_{COD}	Q_{RINT}
S_{PO_4} R2	0.9196	−0.0033	0.9795	−0.0067	0.9851	−0.0082
S_{PO_4} R4	0.0049	0.0726	0.0007	0.0230	0.0006	0.0219
S_{PO_4} R7	0.0383	0.0017	0.0077	0.0007	0.0062	0.0007
S_{NO_3} R4	−0.0003	0.9285	−0.0067	0.9822	−0.0082	0.9848
S_{NO_3} R7	0.0375	0.0003	0.0188	0.0008	0.0162	0.0008
S_{NH_4} R7	0.0000	0.0002	0.0000	0.0000	0.0000	0.0000

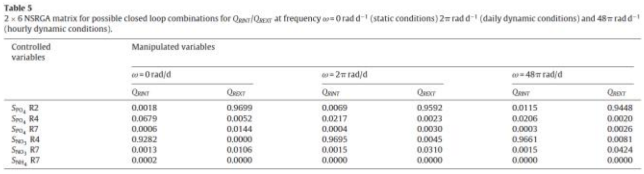


Table 5
2 × 6 NSRGA matrix for possible closed loop combinations for Q_{RINT}/Q_{REXT} at frequency $\omega = 0$ rad d^{-1} (static conditions) 2π rad d^{-1} (daily dynamic conditions) and 48π rad d^{-1} (hourly dynamic conditions).

Controlled variables	Manipulated variables					
	$\omega = 0$ rad/d		$\omega = 2\pi$ rad/d		$\omega = 48\pi$ rad/d	
	Q_{RINT}	Q_{REXT}	Q_{RINT}	Q_{REXT}	Q_{RINT}	Q_{REXT}
S_{PO_4} R2	0.0018	0.9699	0.0069	0.9592	0.0115	0.9448
S_{PO_4} R4	0.0679	0.0052	0.0217	0.0023	0.0206	0.0020
S_{PO_4} R7	0.0006	0.0144	0.0004	0.0030	0.0003	0.0026
S_{NO_3} R4	0.9282	0.0000	0.9695	0.0045	0.9661	0.0081
S_{NO_3} R7	0.0013	0.0106	0.0015	0.0310	0.0015	0.0424
S_{NH_4} R7	0.0002	0.0000	0.0000	0.0000	0.0000	0.0000

Control Structures

Activated sludge: 100 *plus* 1 years
New trends and perspectives

Application of Non-Square Relative Gain Array (NSRGA) to WWTP with EBPR

Internal Model Control (IMC) Tuning of PI/PID controllers

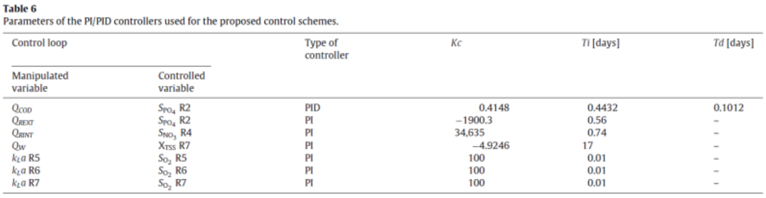


Table 6
Parameters of the PI/PID controllers used for the proposed control schemes.

Control loop		Type of controller	*Kc*	*Ti* [days]	*Td* [days]
Manipulated variable	Controlled variable				
Q_{COD}	S_{PO_4} R2	PID	0.4148	0.4432	0.1012
Q_{REXT}	S_{PO_4} R2	PI	−1900.3	0.56	–
Q_{RINT}	S_{NO_3} R4	PI	34,635	0.74	–
Q_W	X_{TSS} R7	PI	−4.9246	17	–
k_La R5	S_{O_2} R5	PI	100	0.01	–
k_La R6	S_{O_2} R6	PI	100	0.01	–
k_La R7	S_{O_2} R7	PI	100	0.01	–

Model Predictive Control (MPC) of NO3 and NH4 controllers

- MPC architecture uses a linear model of the plant for the prediction of the process variables, over a future finite time horizon, and for the computation of the sequence of future control moves.
- MPC Matlab Toolbox was used for defining these controllers.

Control Structures

Application of Non-Square Relative Gain Array (NSRGA) to WWTP with EBPR

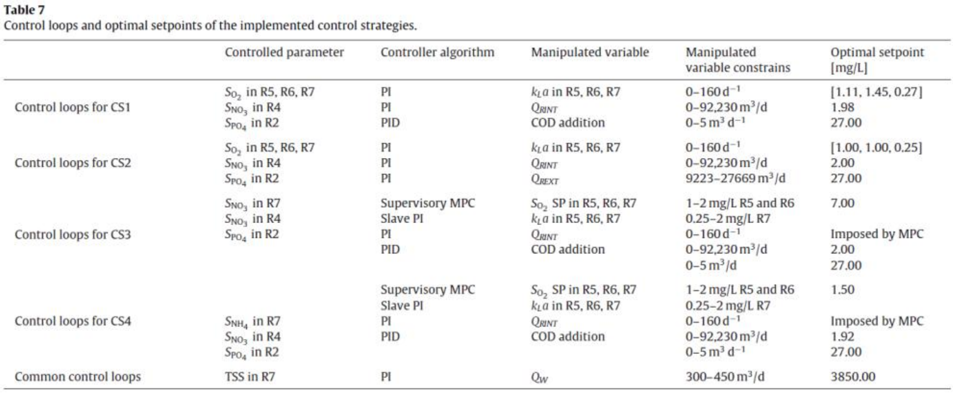
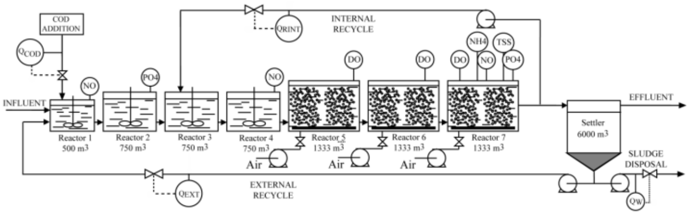


Table 7
Control loops and optimal setpoints of the implemented control strategies.

	Controlled parameter	Controller algorithm	Manipulated variable	Manipulated variable constrains	Optimal setpoint [mg/L]
Control loops for CS1	S_{O_2} in R5, R6, R7 S_{NO_3} in R4 S_{PO_4} in R2	PI PI PID	k_La in R5, R6, R7 Q_{RINT} COD addition	0–160 d^{-1} 0–92,230 m^3/d 0–5 m^3 d^{-1}	[1.11, 1.45, 0.27] 1.98 27.00
Control loops for CS2	S_{O_2} in R5, R6, R7 S_{NO_3} in R4 S_{PO_4} in R2	PI PI PI	k_La in R5, R6, R7 Q_{RINT} Q_{REXT}	0–160 d^{-1} 0–92,230 m^3/d 9223–27669 m^3/d	[1.00, 1.00, 0.25] 2.00 27.00
Control loops for CS3	S_{NO_3} in R7 S_{NO_3} in R4 S_{PO_4} in R2	Supervisory MPC Slave PI PI PID	S_{O_2} SP in R5, R6, R7 k_La in R5, R6, R7 Q_{RINT} COD addition	1–2 mg/L R5 and R6 0.25–2 mg/L R7 0–160 d^{-1} 0–92,230 m^3/d 0–5 m^3/d	7.00 Imposed by MPC 2.00 27.00
Control loops for CS4	 S_{NH_4} in R7 S_{NO_3} in R4 S_{PO_4} in R2	Supervisory MPC Slave PI PI PID	S_{O_2} SP in R5, R6, R7 k_La in R5, R6, R7 Q_{RINT} COD addition	1–2 mg/L R5 and R6 0.25–2 mg/L R7 0–160 d^{-1} 0–92,230 m^3/d 0–5 m^3 d^{-1}	1.50 Imposed by MPC 1.92 27.00
Common control loops	TSS in R7	PI	Q_W	300–450 m^3/d	3850.00



Control Structures

Application of Non-Square Relative Gain Array (NSRGA) to WWTP with EBPR

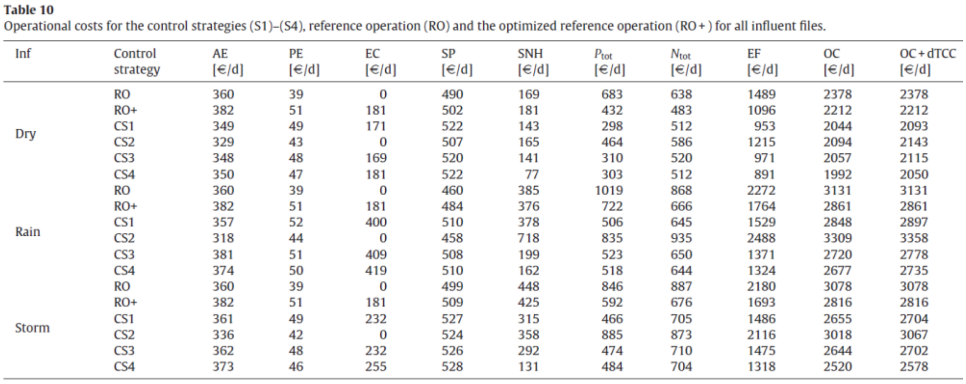


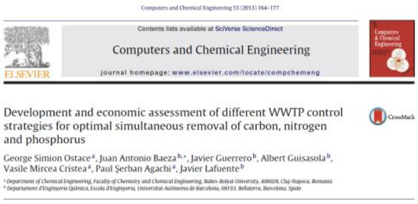
Table 10
Operational costs for the control strategies (S1)–(S4), reference operation (RO) and the optimized reference operation (RO +) for all influent files.

Inf	Control strategy	AE [€/d]	PE [€/d]	EC [€/d]	SP [€/d]	SNH [€/d]	P_{tot} [€/d]	N_{tot} [€/d]	EF [€/d]	OC [€/d]	OC + dTCC [€/d]
Dry	RO	360	39	0	490	169	683	638	1489	2378	2378
	RO+	382	51	181	502	181	432	483	1096	2212	2212
	CS1	349	49	171	522	143	298	512	953	2044	2093
	CS2	329	43	0	507	165	464	586	1215	2094	2143
	CS3	348	48	169	520	141	310	520	971	2057	2115
	CS4	350	47	181	522	77	303	512	891	1992	2050
Rain	RO	360	39	0	460	385	1019	868	2272	3131	3131
	RO+	382	51	181	484	376	722	666	1764	2861	2861
	CS1	357	52	400	510	378	506	645	1529	2848	2897
	CS2	318	44	0	458	718	835	935	2488	3309	3358
	CS3	381	51	409	508	199	523	650	1371	2720	2778
	CS4	374	50	419	510	162	518	644	1324	2677	2735
Storm	RO	360	39	0	499	448	846	887	2180	3078	3078
	RO+	382	51	181	509	425	592	676	1693	2816	2816
	CS1	361	49	232	527	315	466	705	1486	2655	2704
	CS2	336	42	0	524	358	885	873	2116	3018	3067
	CS3	362	48	232	526	292	474	710	1475	2644	2702
	CS4	373	46	255	528	131	484	704	1318	2520	2578

Control Structures

Conclusions of the NSRGA and MPC study

- Four new control approaches for a WWTP with C/N/P removal, with control loops for improving P-removal in addition to the common C/N loops. All the set-points were optimized to ensure optimal performance → the reported results show the highest feasible performance of these control structures with fixed optimized set-points.
- Comparison with all weather influent files with reference operation (open loop except for TSS control) and with optimized reference operation. These results proved that:
  - (i) Operational costs and effluent quality of the WWTP can be greatly improved using model based optimization of the reference operation. Optimized reference operation improved effluent quality and operational costs by 7%-9%.
  - (ii) Automatic control of the WWTP can greatly improve the operational costs of the plant, maintain low pollutant effluent concentrations and achieve a more stable performance.
  - (iii) The Q_{COD} − PO4 R2 control loop (controlled external carbon addition in the first anaerobic reactor) provides a stable EBPR process and produces a better effluent quality.
  - (iv) Using the external recycle flow as manipulated variable to control PO4 at the end of the anaerobic zone proved to be a good approach only under dry weather conditions. The Q_{REXT} − PO4 R2 control loop did not assure a stable performance under rain and storm conditions.
  - (v) CS4 was the most efficient in all working conditions, leading to an operational cost reduction of 120,000 D /year for dry weather conditions. CS3 proved to be the second best due to its good performance during rain and storm events.



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Development and economic assessment of different WWTP control strategies for optimal simultaneous removal of carbon, nitrogen and phosphorus

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