Adaptive modelling of SBRs and effects of model-based optimization on the actual SBR performance

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Outline

- Introduction
- Systematic optimisation protocol
- Evaluation of the protocol
  - Definition of objective(s)
  - Framework of the optimisation
  - Model selection and calibration
  - Scenario analysis
  - Evaluation of the scenario analysis
- Limitations of the model-based optimisation
- Conclusions & perspectives

Introduction

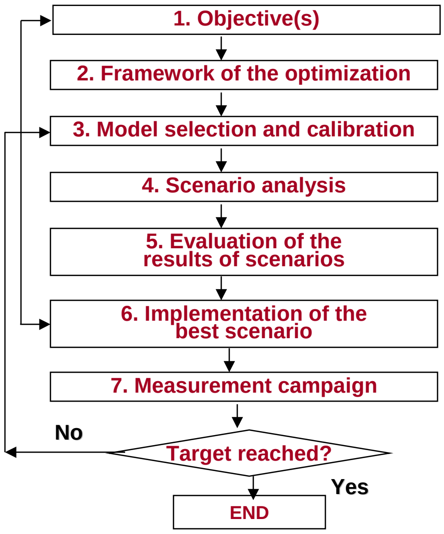
- Both N & P removal successfully demonstrated at lab- and full-scale SBR installations.
- SBR offers more flexibility in operation (compared to continuous systems) – a key aspect in process optimisation.
- Many possible operating strategies to optimise nutrient removal performance in SBRs.
- Usually process developed at lab- or pilot-scale & only comparison of a few operating scenarios
- Increasingly, mathematical models are used to search for the optimal operating scenario (e.g. ASM1 for N-removal and ASM2d for N- & P- removal)

Statement of Objective

- Systematize and standardize the model-based optimisation of SBRs. Important:
  - i. to ensure an objective and detailed search for an optimal operating strategy
  - ii. for internal quality check
  - iii. to compare different optimisation studies

Systematic optimisation protocol

- Objective oriented & iterative protocol
- A grid of scenarios (full-factorial design) built on the basis of the degrees of freedom and the constraints of the SBR system
- Selection and calibration of a suitable model to describe the biological processes
- Simulation and evaluation of a multitude of scenarios
- Selection of the best scenario
- Implementation & final evaluation



Evaluation of the systematic protocol
1. Objective

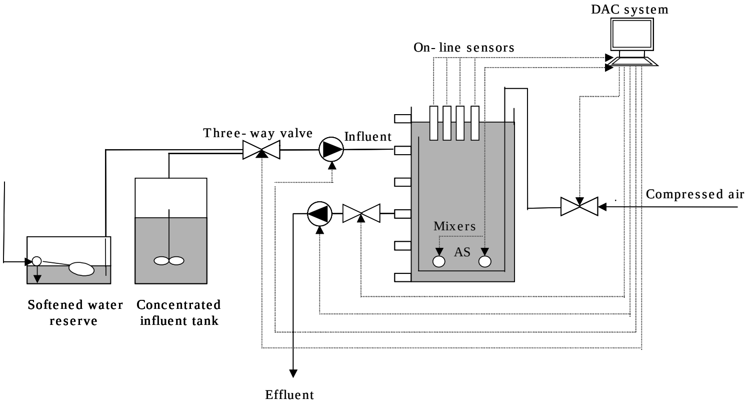
- Improved and robust N and P removal in a nutrient removing SBR

2. Framework of the optimisation

- *The SBR system:*
  - A lab-scale reactor with 80 L treating a synthetic wastewater

2. Framework of the optimisation *cont'd.*

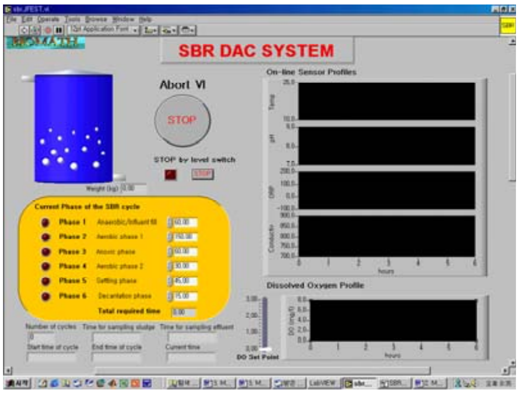
- *The SBR system:*
  - A lab-scale reactor with 80 L treating a synthetic wastewater



2. Framework of the optimisation *cont'd.*

- *The SBR system:*
  - A lab-scale reactor with 80 L treating a synthetic wastewater

LABVIEW Data-acquisition and Control



2. Framework of the optimisation *cont'd.*

- *Characteristics*
  - V= 80 l
  - SRT= 10 d, HRT = 12h
  - synthetic influent (COD/N/P = 100/13,7/2,14) similar to municipal wastewater
  - 4 cycles per day (6 hours)

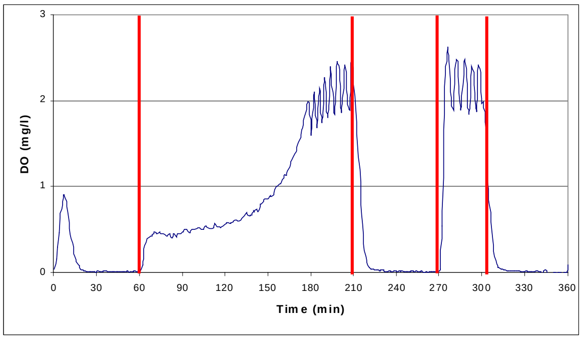
Anaerobic	Aerobic 1	Anoxic	Aerobic 2	Settling	Draw
60 min	150 min	60 min	30 min	45 min	15 min

- *Measurements*
  - DO, pH, ORP, conductivity, weight (on-line - minute)
  - COD, CODsol, Total-N, NH_4, NO_3, NO_2, PO_4 (off-line - daily)
  - MLSS (2-3 g/l), SVI (80-120 ml/g) (off-line - daily)
  - DGGE (microbial community) (off-line - weekly)

2. Framework of the optimisation *cont'd*

- *The SBR system: Typical process data*

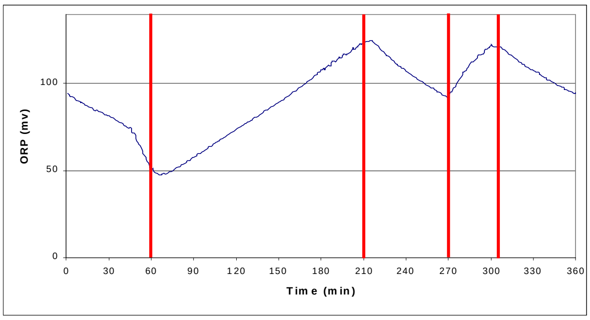
  Dissolved oxygen



2. Framework of the optimisation *cont'd*

- *The SBR system: Typical process data*

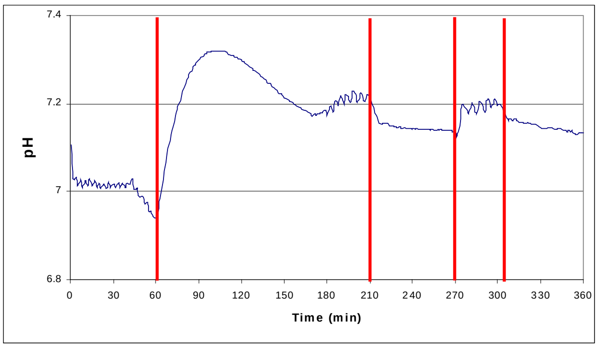
  Redox potential (aeration +, denitrification -)



2. Framework of the optimisation *cont'd*

- *The SBR system: Typical process data*

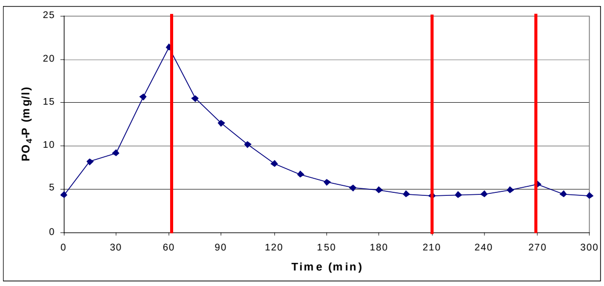
  pH



2. Framework of the optimisation *cont'd*

- *The SBR system: Typical process data*

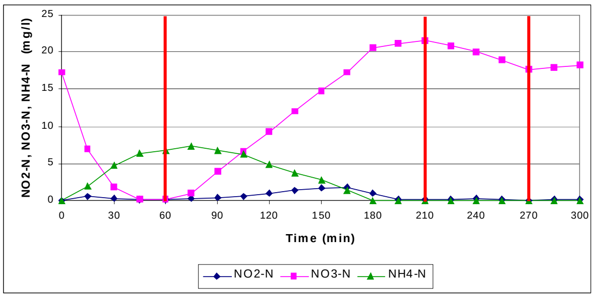
  Phosphate



2. Framework of the optimisation *cont'd*

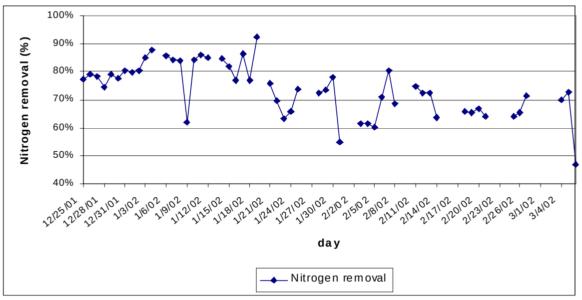
- *The SBR system: Typical process data*

  Nitrogen fractions (NH_4, NO_3, NO_2)



2. Framework of the optimisation *cont'd.*

- *Performance:*
  - 95 % COD-removal
  - 65 % N-removal
  - complete nitrification / incomplete denitrification
  - 65 % PO_4-removal (limited because of nitrate presence)



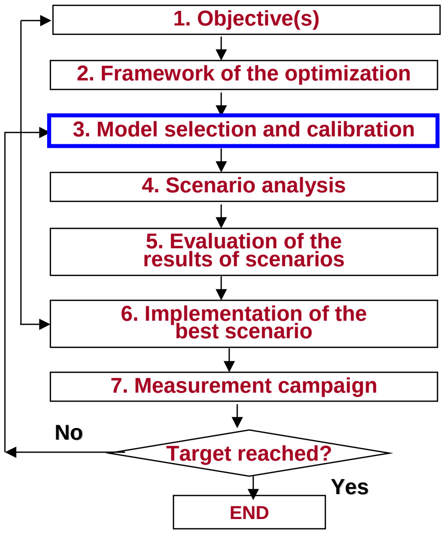
2. Framework of the optimisation *cont'd.*

- *The SBR system:*
  1. A lab-scale reactor with 80 L treating a synthetic wastewater
- *Degrees of freedom (based on systems-analysis)*
  1. Oxygen set-point (S_O-sp)
  2. Length of the anaerobic phase (T_{ANB})
  3. Length of the reaction (aerobic + anoxic) (T_R),
  4. Step-feed of the influent to anoxic periods ($V_{step\text{-}feed}$)
  5. Intermittent aeration frequency during the react phase
     i.e. more than 1 aerobic/anoxic phase per SBR cycle of 6 hours

2. Framework of the optimisation *cont'd.*

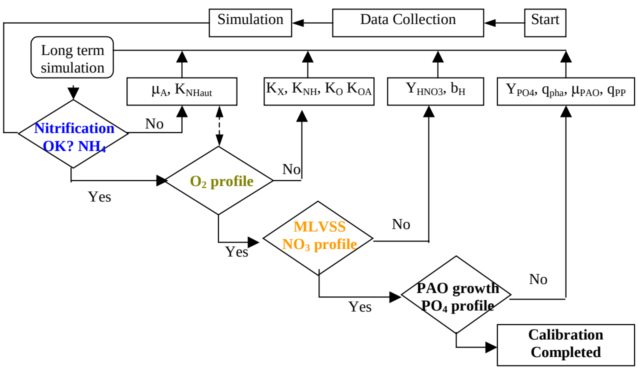
- *Constraints*
  1. Total volume (80 L)
  2. The volumetric exchange ratio, $V_{initial}/V_{total}$ (0.5)
  3. SRT (10 d) & HRT (12 h)
  4. The total cycle length (360 min)
  5. The $K_L a$ is sufficiently high *to ensure oxygen at set-point value*
  6. The settling/draw phase fixed (60 min)

Systematic optimisation protocol



3. Model selection and calibration

- *Selected model:*
  ASM2d extended with hydrolysis of organic nitrogen module of ASM1
- *Systematic calibration procedure:*



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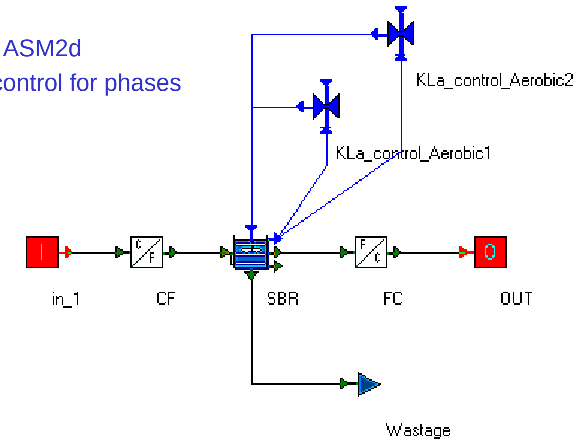
3. Model selection and calibration

- *Model implementation:*
  in WEST® with
  - extended ASM2d
  - aeration control for phases



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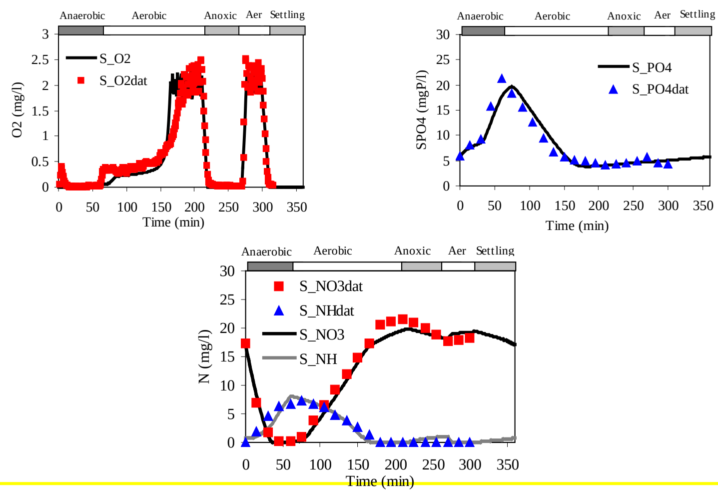
3. Model selection and calibration *cont'd.*

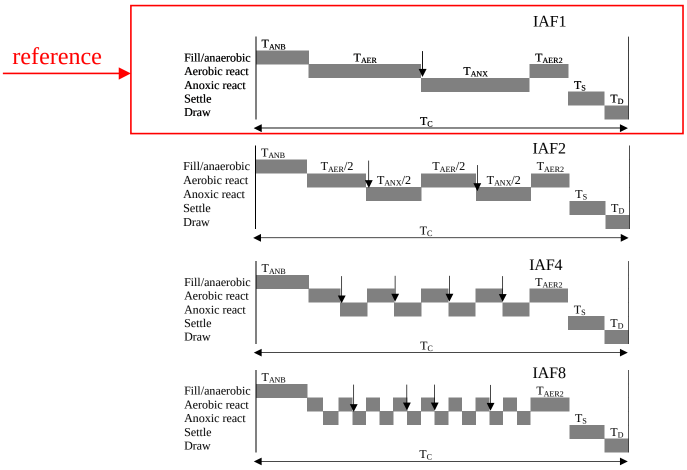
- *Calibration results:*



4. Scenario analysis

- Formulation of grids of scenarios:

Configuration of intermittent aeration frequencies & step-feed of influent (↓)



4. Scenario analysis *cont'd.*

- Construction of grids of scenarios
  - Choose a range and interval for the degrees of freedoms
    - S_O-sp: [0.2, 0.4, 0.6, 0.8, 1.0]
    - $V_{step\text{-}feed}$: [0, 5, 10]
    - T_{ANB}: [60, 70, 80]
    - T_{AER}: [130, 140, 150]
    - Intermittent aeration frequency:[1, 2, 4, 8]
  - Full-factorial design of degrees of freedoms:

    ➔ total <u>648</u> scenarios
  - Simulate each scenario for 3 X SRT, in this case 30 days

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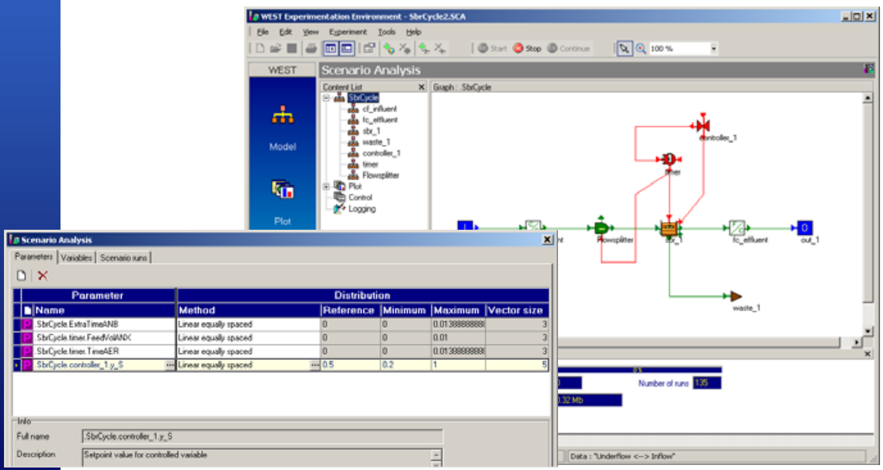
4. Scenario analysis *cont'd.*

- WEST Scenario analysis tool



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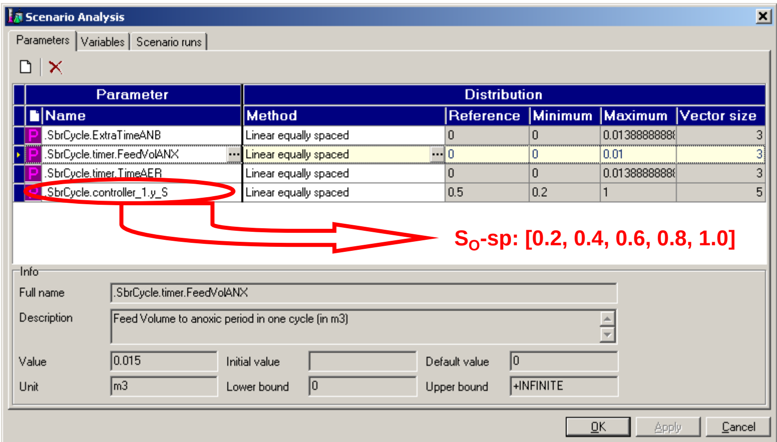
4. Scenario analysis *cont'd.*

- WEST Scenario analysis tool: Scenario generator



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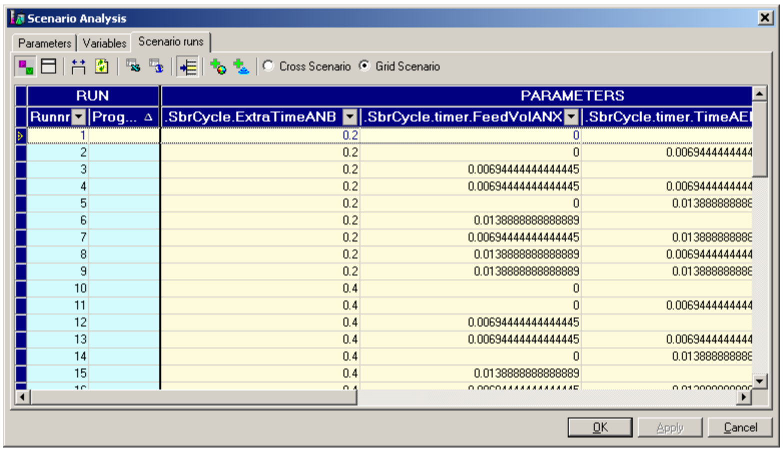
4. Scenario analysis *cont'd.*

- WEST Scenario analysis tool: Scenario results window



Scenario Analysis

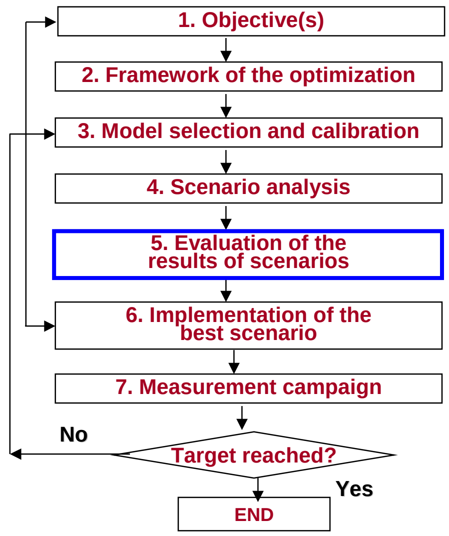
Parameters | Variables | Scenario runs

Cross Scenario / Grid Scenario

RUN		PARAMETERS		
Runnr	Prog...	.SbrCycle.ExtraTimeANB	.SbrCycle.timer.FeedVolANX	.SbrCycle.timer.TimeAE
1		0.2	0	
2		0.2	0	0.0069444444444
3		0.2	0.00694444444444445	
4		0.2	0.00694444444444445	0.0069444444444
5		0.2	0	0.013888888888
6		0.2	0.0138888888888889	
7		0.2	0.00694444444444445	0.013888888888
8		0.2	0.0138888888888889	0.0069444444444
9		0.2	0.0138888888888889	0.013888888888
10		0.4	0	
11		0.4	0	0.0069444444444
12		0.4	0.00694444444444445	
13		0.4	0.00694444444444445	0.0069444444444
14		0.4	0	0.013888888888
15		0.4	0.0138888888888889	

OK | Apply | Cancel

Systematic optimisation protocol



5. Evaluation of the scenarios

- Effluent quality

  Effluent quality of 648 scenarios were analysed

  Conclusions:

  - Increasing T_{ANB} improves P-removal but decreases N-removal
  - Increasing T_{AER} slightly improves the nitrification but has a negative effect on denitrification.
  - The S_O-sp dictates the overall behaviour of the system.
  - Step-feed has a positive effect on the denitrification.
  - Increasing the intermittent aeration frequency (IAF) increases N & P removal

5. Evaluation of the scenarios *cont'd.*

- Robustness index (Vanrolleghem & Gillot, 2002)
  - Inverse of sensitivity of a system towards a change in operating conditions.

$$RI = \left(\sqrt{\frac{1}{p} \sum_{i=1}^{p} S_i^2} \right)^{-1} \quad \text{where } S_i = \frac{dCost}{d\theta_i} \cdot \frac{\Delta\theta_i}{Cost} \quad i = 1..p \text{ and } Cost = [TN, PO_4]$$

    - High value of RI (low sensitivity) means high robustness
  - The following changes were manipulated in the SBR system:
    - SRT (-10%)
    - HRT (+10%)
    - Influent COD load (-10%)
    - Temperature (-33%)

5. Evaluation of the scenarios *cont'd.*

- RI calculated for each operating scenario, general conclusions:
  - RI conflicts with effluent quality:
    e.g. the robustness peaks when the S_O-sp of the SBR is 0.2, but at this point the effluent quality is worst.
  - N-removal is most sensitive towards a change in temperature
  - P-removal is most influenced by the influent COD-load
  - The reference system provided the highest robustness for N-removal
  - The best scenario in IAF4 provided the most robust P-removal

5. Evaluation of the scenarios *cont'd.*

- Selection of the best scenario (BSC)
  - Effluent quality and robustness criteria conflict

    ➔ A compromise is needed
  - Optimal operation under IAF4 is chosen:
    - provides effluent quality below discharge standards
    - accompanied with good system stability.
  - The N & P removal is improved by 54% and 74% respectively.

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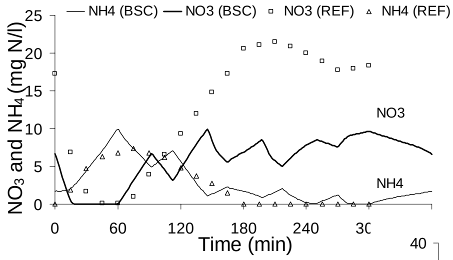
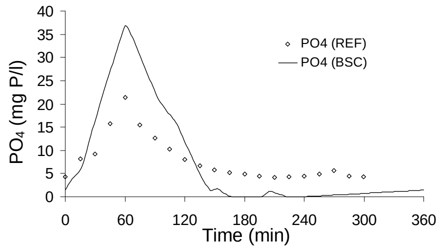
5. Evaluation of the scenarios *cont'd.*

- Simulation of best scenario: 4 aeration phases



Total Nitrogen: 50% lower



PO_4 conc. < 1 mg/l

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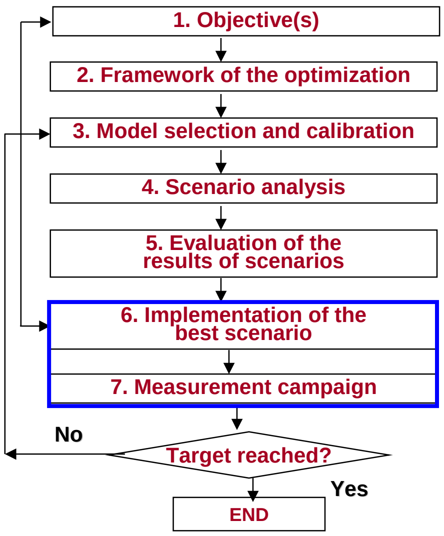
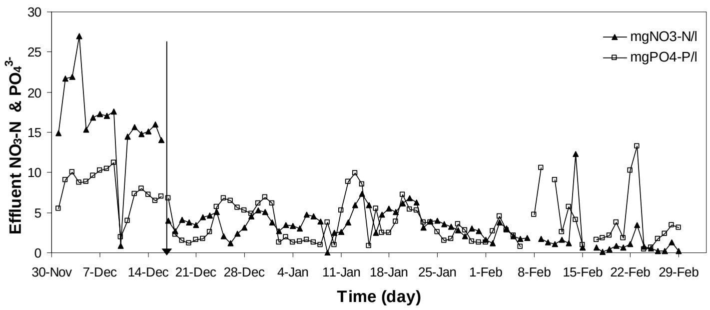
Systematic optimisation protocol



Implementation

- Nutrient removal results



Beautiful, better than expected !

Implementation (cont'd)

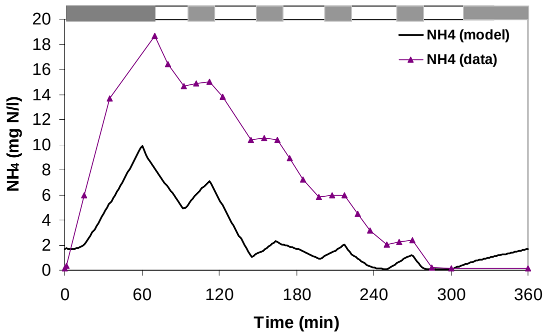
- Nutrient removal results

	Total Nitrogen mgN/l	NH_4-N mgN/l	NO_3-N mgN/l	PO_4-P mgP/l
Influent	60	5	0	11
Effluent concentrations				
Model prediction	**8.4**	**1.7**	**6.7**	**1.5**
Reference operation	18.1	0.1	12.5	6.6
Optimal operation	8.6	1.1	3.1	3.8
Removal efficiency				
Reference operation	70%	-	-	48%
Optimal operation	86%	-	-	65%
Improvement	+53%	-	+76%	+43%

Indeed, better than expected !

Measurement campaign + Model validation

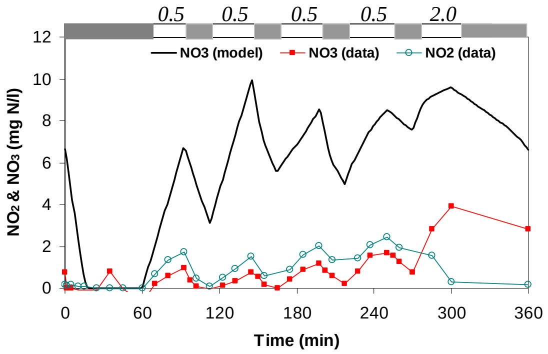
- Ammonia trajectory:



No more ammonification !

Measurement campaign + Model validation

- Nitrate trajectory:



Nitrite accumulation !

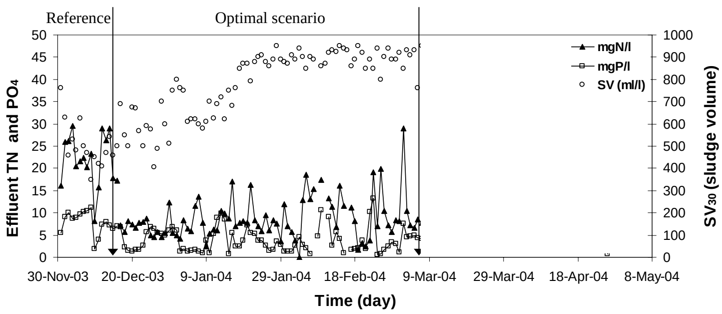
Model validation

- Ammonification is no longer limiting process
- Nitrite is accumulating in aerobic phase
  - 2nd step nitrifiers have lower oxygen affinity (higher K_O)
  - Alternating aeration is inhibitory for 2nd step nitrifiers
- ==>Nitrogen removal over nitrite

- Model adaptation necessary
  - Back to ASM2d (no more ASM1-ammonification process)
  - 2-step nitrification (NH_4 --> NO_2 --> NO_3 : X_{N1}, X_{N2})
  - 2-step denitrification (NO_3 --> NO_2 --> N_2 : X_H)

Measurement campaign

- Sludge volume

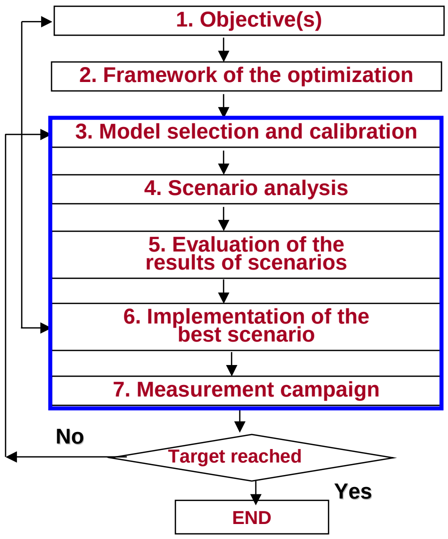


Filamentous bulking !

Next iteration

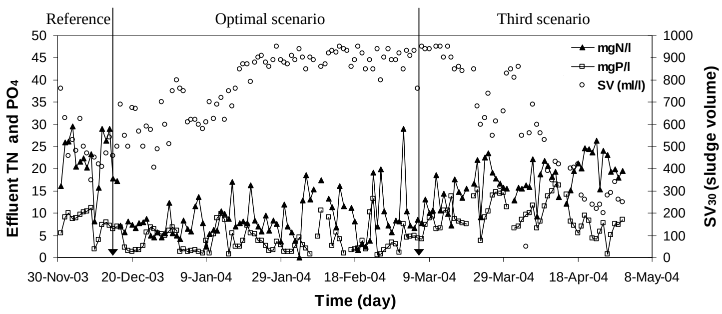
- DO set-points to 1 mg/l
- Influent Ca^{++}/Na^{+} - ratio increased (Higgins & Novak, 1997)

- Expectation 1:
  Decreased nutrient removal
- Hope:
  Improved settling properties



Measurement campaign

- Settling improves
- Nutrient removal worse



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Measurement campaign

- Nutrient removal results:

	COD mgCOD/l	Total nitrogen mgN/l	PO_4-P mgP/l
Influent	**410**	**60**	**11**
Removal efficiency			
Reference operation (1 year average)	**91%**	**56%**	**18%**
Optimal Operation (2.5 months average)	**94%**	**86%**	**65%**
Third operation (2 months average)	**92%**	**72%**	**20%**

No more Bio-P removal (NO_3-inhibition)

- We're back to where we started …
- It's not always success stories !

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Limitations of model-based optimisation

- Settling properties of activated sludge are not predicted by the model
  - No unified mechanistic model available to predict filamentous bulking or pin-point settling issues in activated sludge.
  - However, expert knowledge may be incorporated at the decision making step to account for this unknown factor
- Changing system operation may alter the microbial population thereby resulting in a change of the kinetic & stoichiometric parameters of the model + a change in model structure.
  - To account for this, iterate the systematic calibration protocol & re-calibrate the model and reconstruct the model if necessary until the objective of the optimisation is satisfied.

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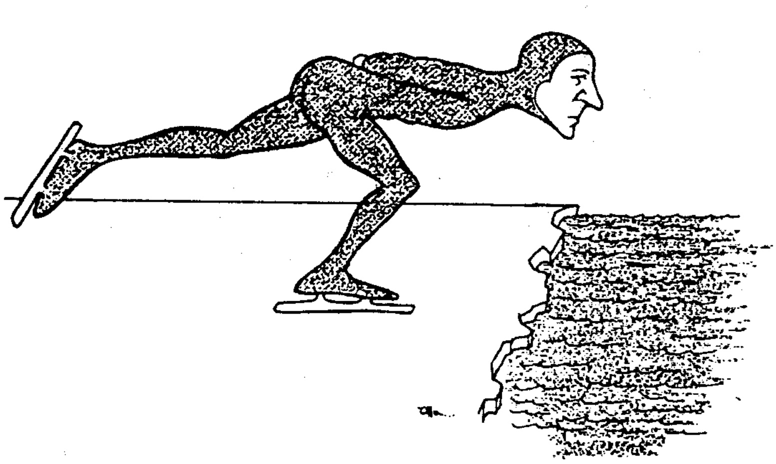
"Do not extrapolate with your model"



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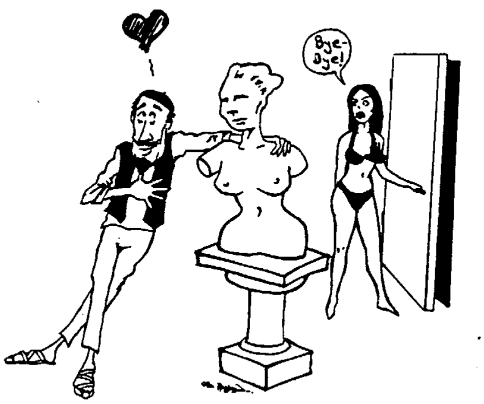
"Do not fall in love with your model"



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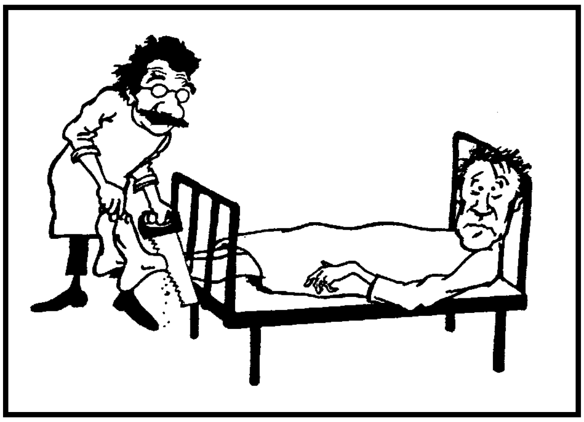
“Do not adjust reality to your model”

- Procrustes’ bed



Conclusions & Perspectives

- A systematic protocol for model-based optimisation of SBRs is developed and successfully (?) evaluated at a lab-scale SBR to achieve optimal N & P removal.
- Step-feeding of influent improves denitrification
  => reduces negative NO_3-N effect on P-removal
- Frequent intermittent aeration at low DO during react phase is positive for overall N & P-removal
- Unmodelled phenomena should always be considered and require adaptive modelling (parameter + structure change)
- The systematic protocol is made flexible and objective oriented which can be used for different activated sludge systems
- Software support makes such scenario evaluation easy.