Bits and Bytes and Bugs

On Monitoring and Control in WRRF's (aka WWTPs)

Smart Wastewater Virginia WEA Seminar

Richmond, VA

May 1st 2014

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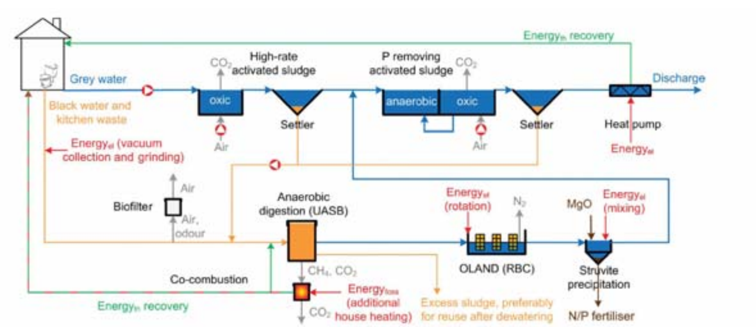
WRRF's

- Water resource recovery facility



Scheme of source-separated sanitation implementing energy and nutrient recovery as practised for 32 houses in Sneek

Verstraete & Vlaeminck (2011) Int. J. Sust. Dev. World Ecol., 18, 253-264.

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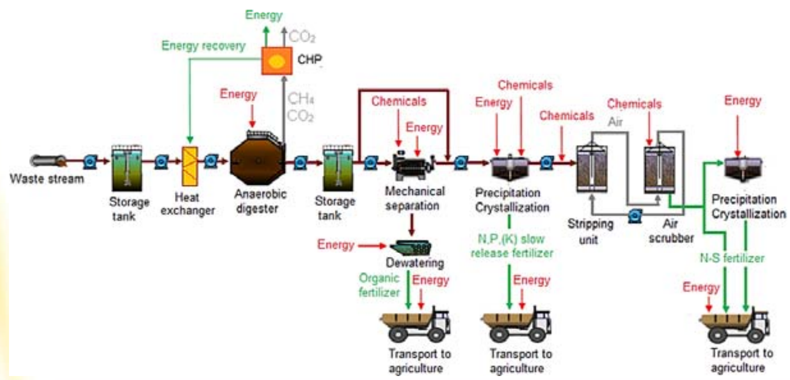
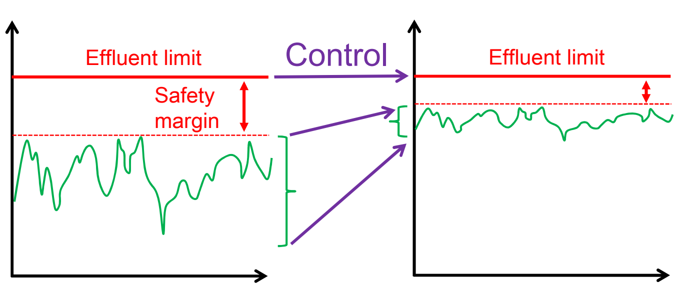
WRRF's

- Water resource recovery facility



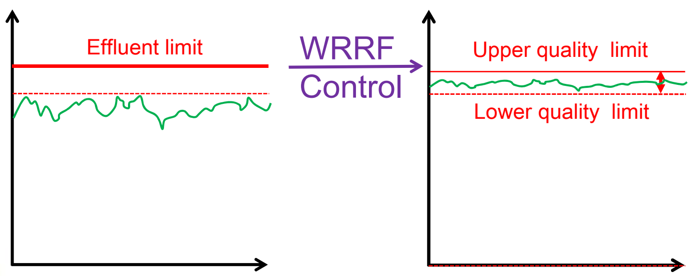
Control challenges

- What control brings:



Control challenges

- Paradigm shift with WRRFs:



Control challenges

- Much stricter product specifications!

Control challenges

- No more forgiving client

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Control challenges

- No selection of raw materials

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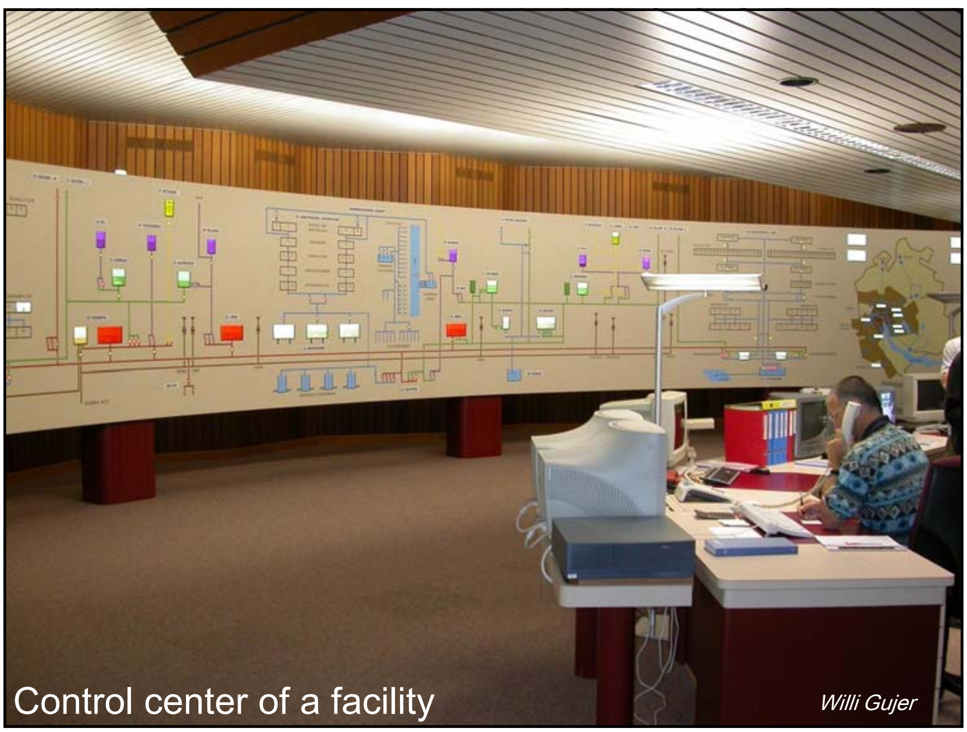
Overview

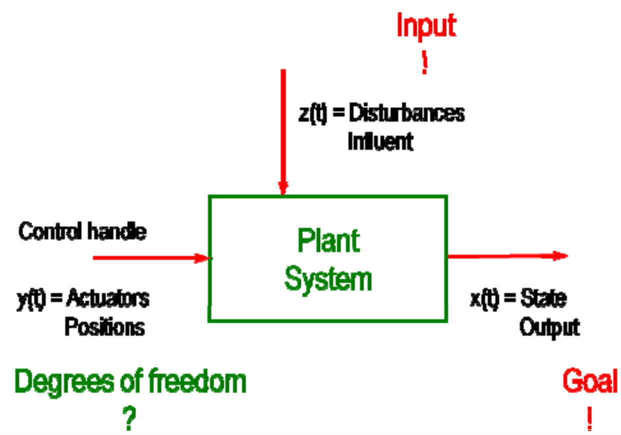
- WRRF's – the new control objectives
- The control loop
  - Control
  - Sensors
  - Actuators
  - Models and control
- Data quality
- Conclusions



Control center of a facility

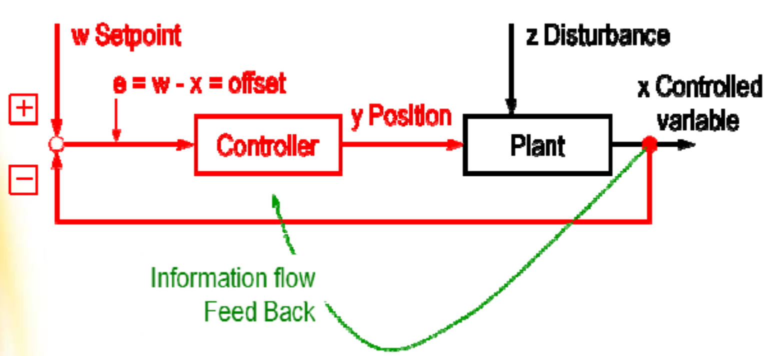
Willi Gujer

The control problem



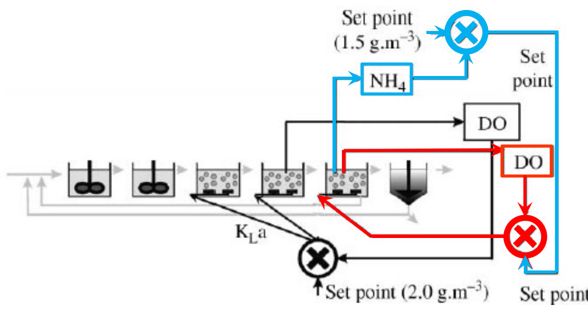
Feedback control

$y = f(x,w,t)$

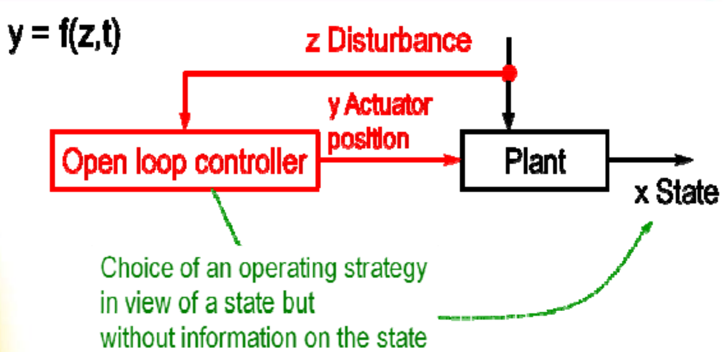


FB control – An example

- Dissolved oxygen FB control
- Cascade ammonia FB control



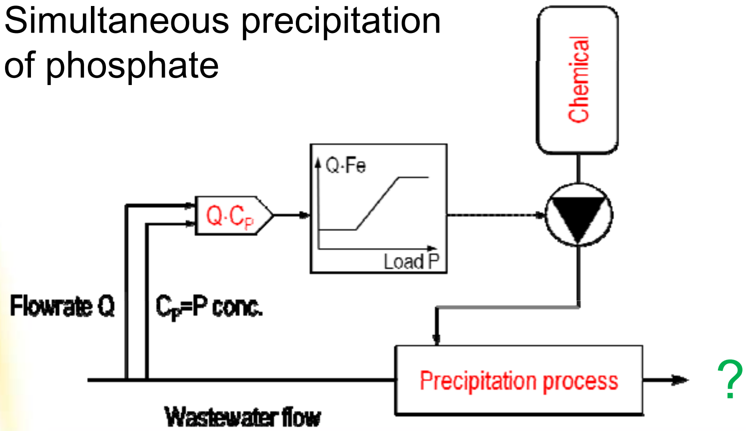
Feedforward control



Example: Phosphate - precipitation

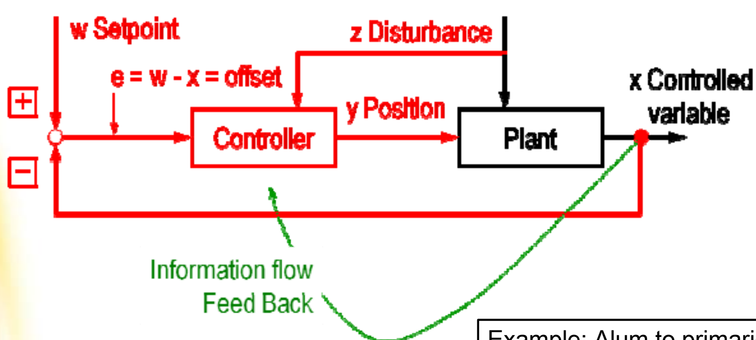
FF control – An example

- Simultaneous precipitation of phosphate



Feedforward/feedback control

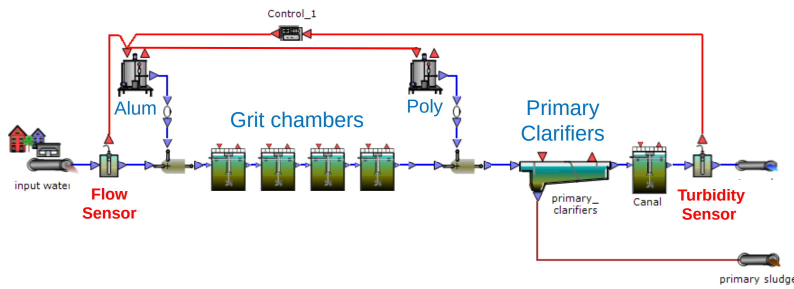
y = f(x,w,z,t)



Example: Alum to primaries

FF/FB control – An example

- CEPT – Alum/polymer addition based on
  - Effluent turbidity (Feedback – control objective)
  - Influent flow rate (Feedforward – disturbance)



Tik et al. (2013) ICA2013, Narbonne, France

Overview

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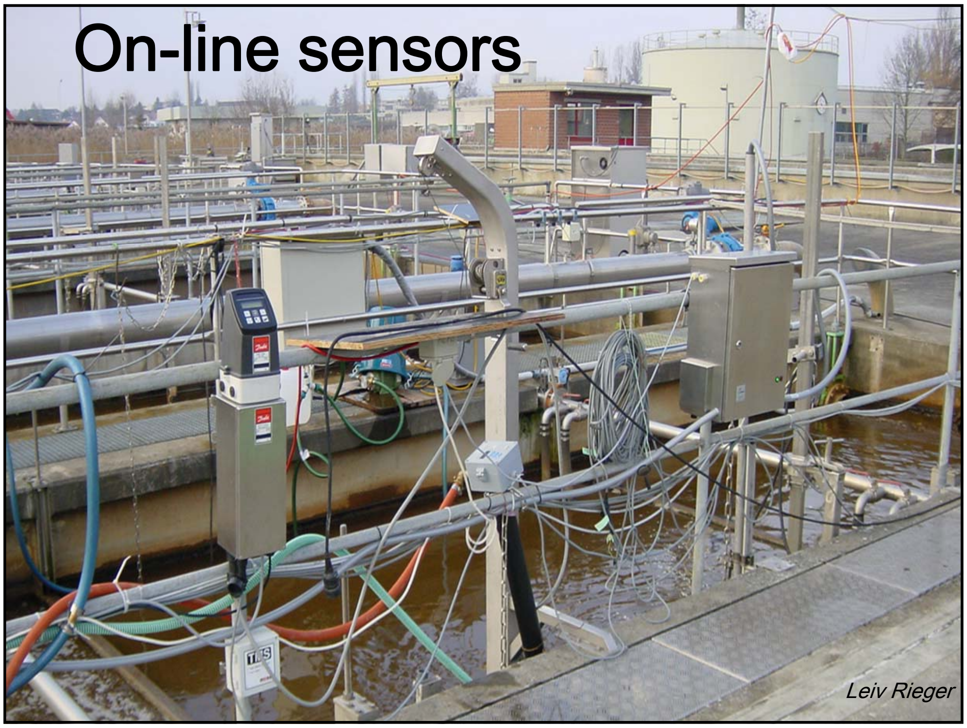
On-line sensors



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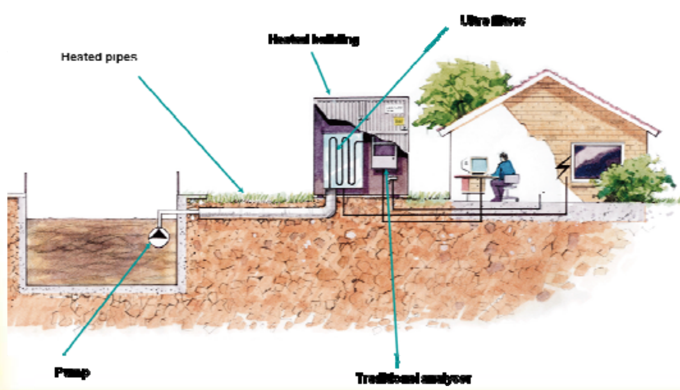
Types of sensors

- On-line sensors (analyzers)



Pernille Ingildsen

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Types of sensors

On-line sensors - Analyzers

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Types of sensors

On-line sensors - Filtration units

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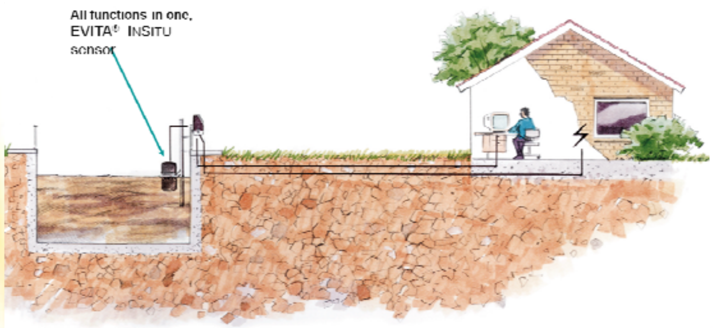
Types of sensors

- In situ sensors ("probes")



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Types of sensors

In situ sensors

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Sensors overview

- Physical properties

Variable	Process	Application Level
Temperature	General	All
Pressure	General	All
Liquid level	General	All
Flow rates	General	All
Suspended solids	General	Often
Sludge blanket	Settler	Few
UV/VIS (NO_3, NO_2)	General	Often
UV/VIS (COD, TOC, TKN)	General	Few

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Sensors overview

- Chemical properties (1)

Variable	Process	Application Level
pH	General	All
Conductivity	General	All
Oxygen	AS, BNR	All
Redox - ORP	AD, BNR	Often
NH_4^+ (electrode)	BNR	Often
NO_3^- (electrode)	BNR	Few
Biogas (CH_4, H_2S, H_2)	AD	Few
CO_2 N_2O (off-gas)	AD, AS, BNR	Few

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Sensors overview

- Chemical properties (2)

Variable	Process	Application Level
COD (analyser)	AD, AS, BNR	Few
TOC (analyser)	AD, AS, BNR	Few
TN (analyser)	AD, AS, BNR	Few
NH_4^+ (analyser)	BNR	Often
NO_3^- (analyser)	BNR	Often
PO_4^{3-} (analyser)	BNR	Often
TP (analyser)	BNR	Few
Bicarbonate	AD, BNR	Few
Volatile Fatty Acids	AD, BNR	Development

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Sensors overview

- Biological properties

Variable	Process	Application Level
Respiration rate	AS, BNR	Few
Toxicity	AD, AS, BNR	Few
rbCOD	AS, BNR	Few
NO/N_2O^- (μ-biosensor)	BNR	Development

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Sensors

- So, what's new?
  - Optical DO
  - UV/VIS spectroscopy
  - Ammonia sensor with compensations
  - Autoclean
    - Airbrush
    - Wiper
    - Ultrason

Overview

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Actuators

Actuators

- Many!
- Maybe not in diversity, but in numbers

- Challenges:
  - What sensor to connect to what actuator
    → Control Structure Design
  - Not all have the same control authority

What can be manipulated directly?

- Flow rates (pumps / valves)
  - RAS
  - WAS
  - Internal recycles
  - Reject water streams
  - Inflow from sewer system
- Air flow rate
- Aerated volume
- Addition of chemicals

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What can be manipulated indirectly?

- DO concentration
- Sludge concentration
- Sludge age
- Biomass population

→ the “bugs”

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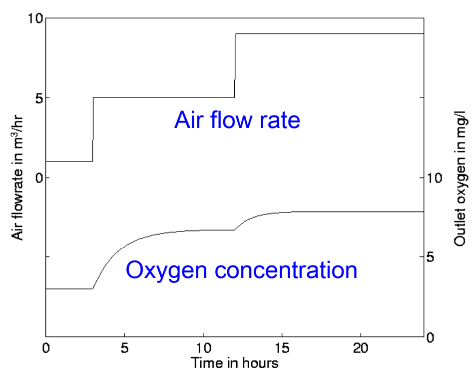
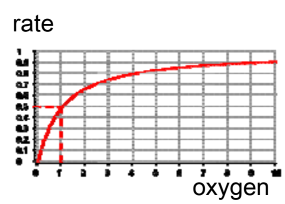
Actuator characteristics

- Often non-linear
  - Pumps
  - Valves
- Often only “one-way”
  - Addition of chemicals
  - Air
- Indirect
  - Biomass population
- Limited actuator action → “Control authority”
  - Aeration, chemicals, flows

Actuator characteristics

- Limited control authority





On top of that: Monod kinetics lead to reduced impact a

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Models and controllers

- Software sensors = data + model (e.g. toxicity)
- Model embedded in feedforward controller
- Model simulation to evaluate controllers
- Optimize the settings of a controller (tuning)
  - Using a complex model (ASM)
  - Using a simple model

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Model simulation for controller eval.

- Practical problems of a comparative field study:
  - Comparison in time doesn't work
    due to time-variation in the process
  - Parallel lanes are not really the same

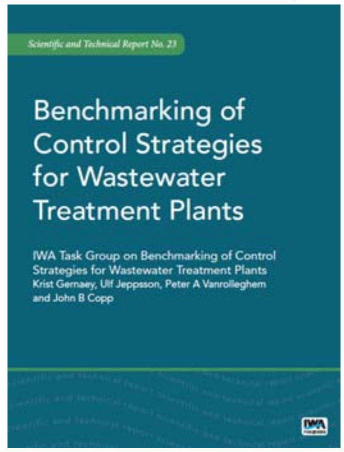
Model simulation for controller eval.

- What to do?
  - Simulate !
  - Realistically !
  - Dynamically ! (we're talking about control after all)
  - Crazy ideas are allowed, no damage done…
  - Repeatable results ==> differences more clear

This is what is called: Benchmarking

Simulation-based Benchmarking

- Initial idea:
  º1993, Bengt Carlsson
- º2005, IWA Task Group on Benchmarking of Control Strategies for WWTPs
- 100 contributors



Models and controllers

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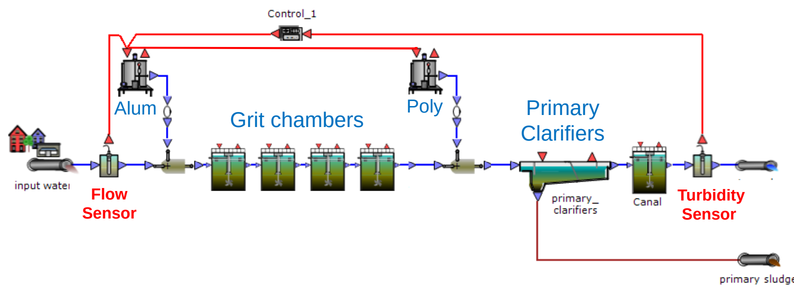
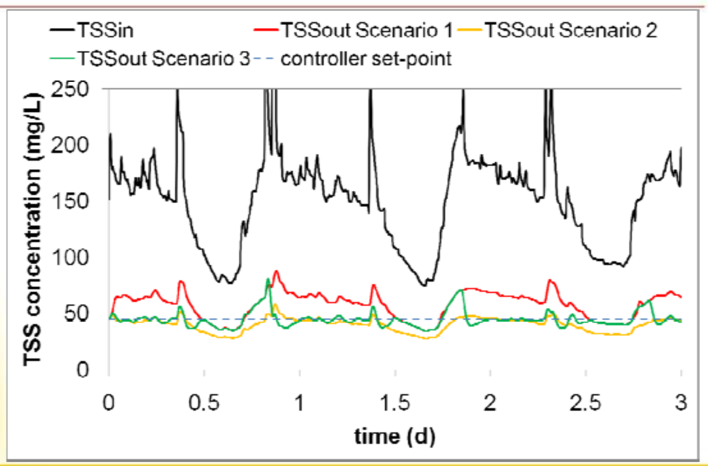
Model use for controller tuning

- CEPT – Alum/polymer addition (FB control)
- Full primary clarifier / grit chamber model



Tik et al. (2013) ICA2013, Narbonne, France

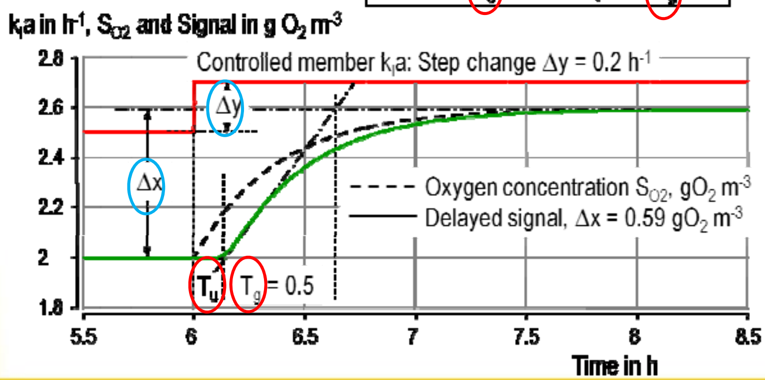
Model use for controller tuning



Modeling for controller optimization

- Cohen-Coon method:

Proportionality coefficient $K_S = \Delta x / \Delta y$
Dead time T_u Transitory time T_g



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Modeling for controller optimization

- Cohen-Coon PID tuning rules

Type of controller	K_P Gain	$T_I = \frac{K_P}{K_I}$ Reset time	$T_D = \frac{K_D}{K_P}$ Rate time
P	$\frac{T_g}{K_S \cdot T_u}$	-	-
PI	$0.9 \cdot \frac{T_g}{K_S \cdot T_u}$	$3.3 \cdot T_u$	-
PID	$1.2 \cdot \frac{T_g}{K_S \cdot T_u}$	$2 \cdot T_u$	$0.5 \cdot T_u$

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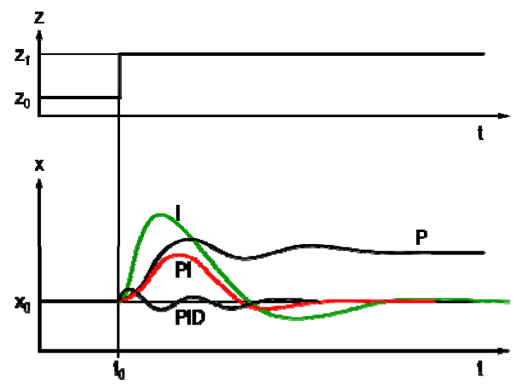
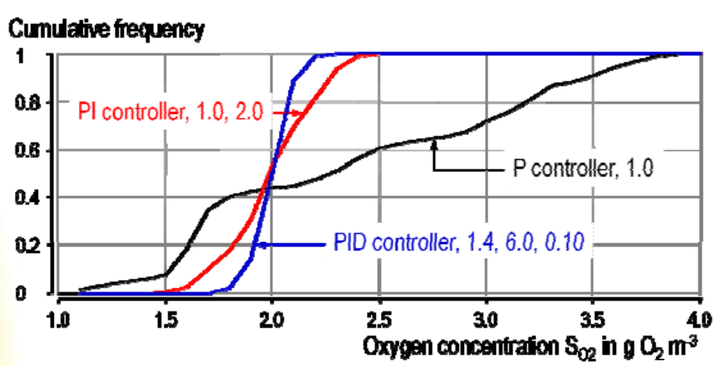
Modeling for controller optimization

- Performance for disturbance rejection

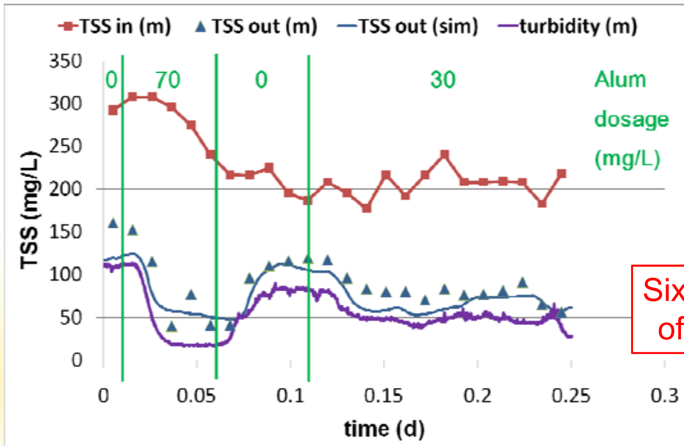


Modeling for controller optimization

- Performance difference between controllers



Cohen-Coon tuning of alum controller



Six hours of work

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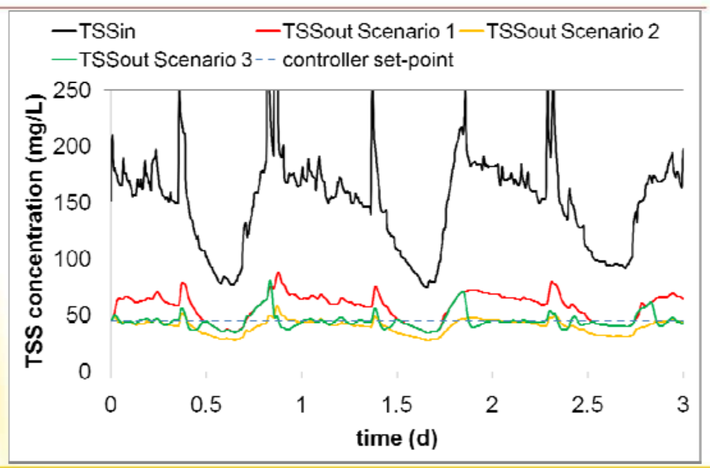
Performance alum/poly FB controller



Scenario 3 uses 30% less alum than scenario 2

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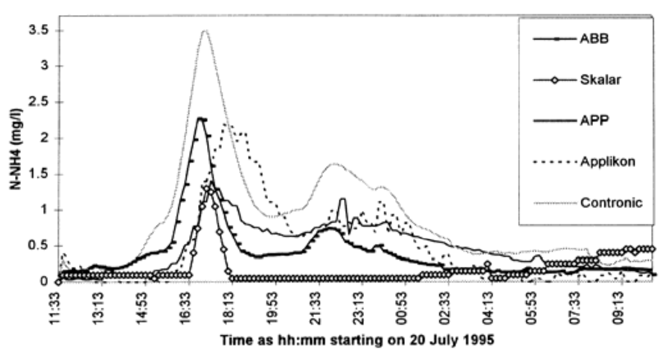
Data quality

- Wacheux et al. (1996) – Ammonia sensors



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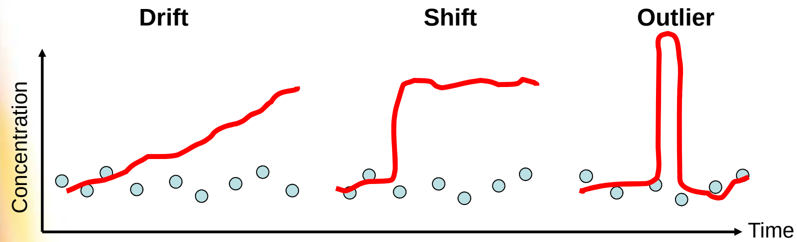
Data quality

- Systematic measurement errors



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Data collection : Weekly maintenance + Air Cleaning

- Increase cleaning frequency
  until time has no effect on data quality

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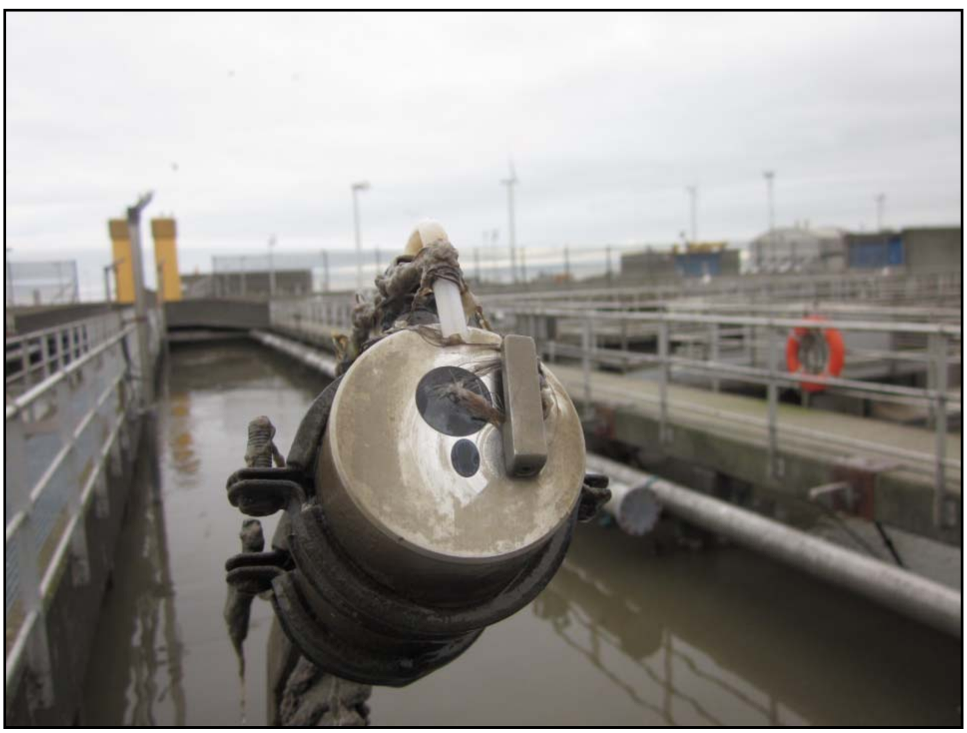
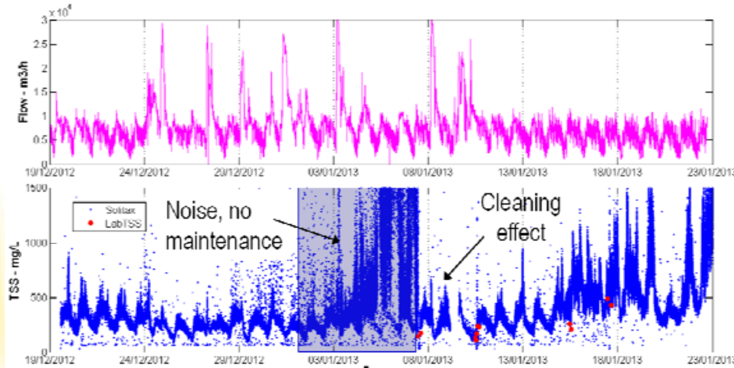


Data collection :
Weekly maintenance + Air Cleaning

- Effect of hair on wiper (raw data at PC inlet)



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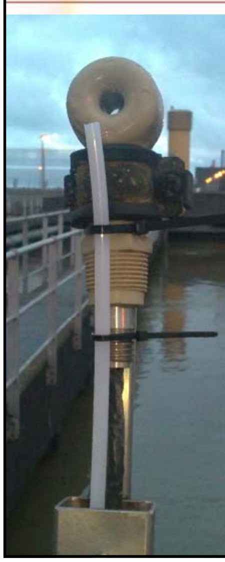
Data collection :
Weekly maintenance + Air Cleaning



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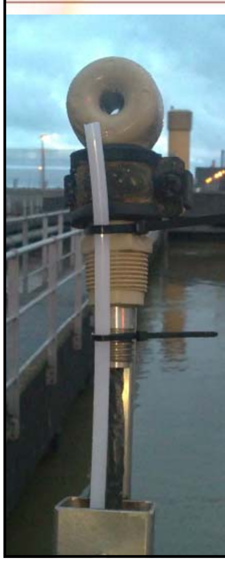
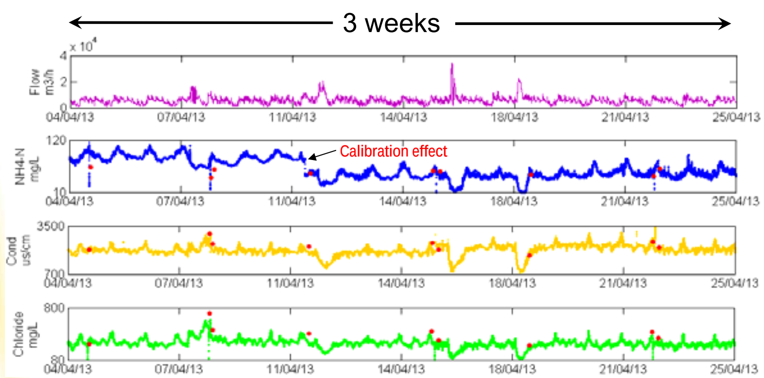


Data quality assessment - I

- Quality control measurements - recalibration



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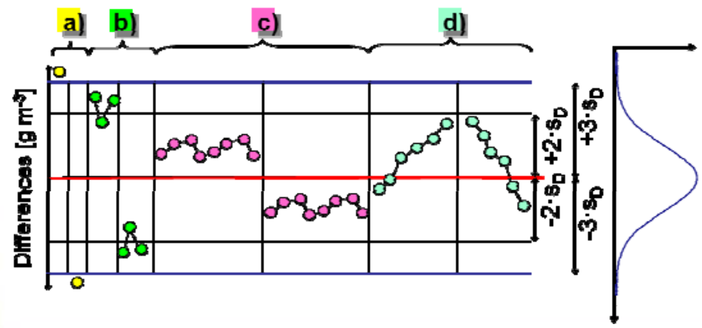
Data quality assessment - I

- Shewhart control charts
  (comparison of sensor and sample data)



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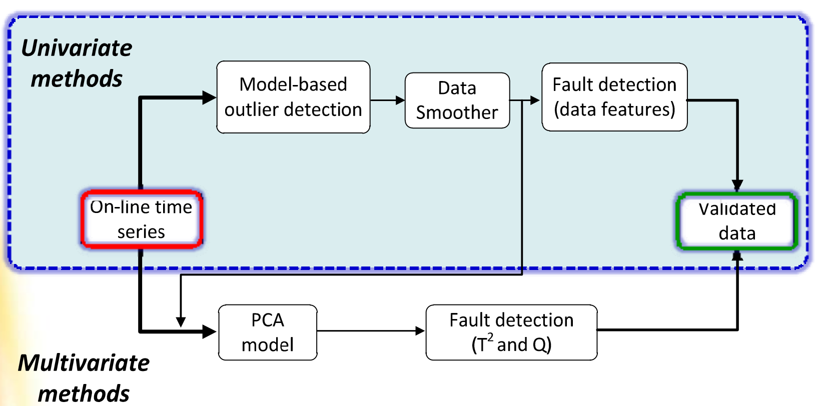
Data quality assessment - II



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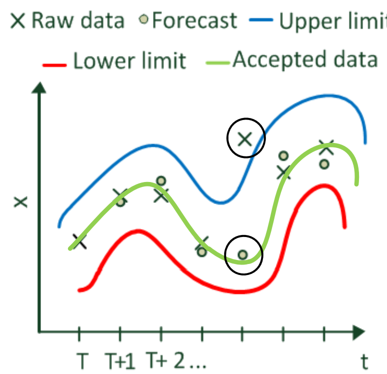
Data quality assessment - II

- Univariate methods
  - Outlier detection
  - Autoregressive models
  - At T forecasting (T+1):
    - variable $\hat{x}$
    - std of error $\hat{\sigma}_e$
  - Prediction interval:

$$x_{\lim} = \hat{x} \pm K \cdot \hat{\sigma}_e$$



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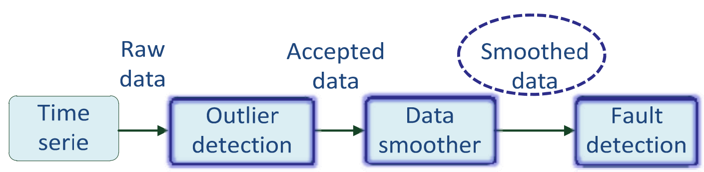
Data quality assessment - II

- Univariate methods



  - Fault detection
    - % replaced data (outliers) --» data goodness
    - Slope --» rate of change
    - Residuals correlation --» good fit of model
    - Residuals standard deviation (RSD) --» variance

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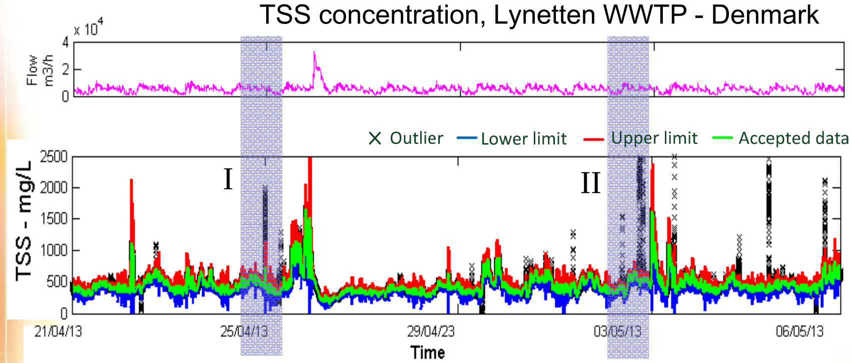
Data quality assessment - II

- Univariate analysis – An example



... some outliers and doubtful data identified

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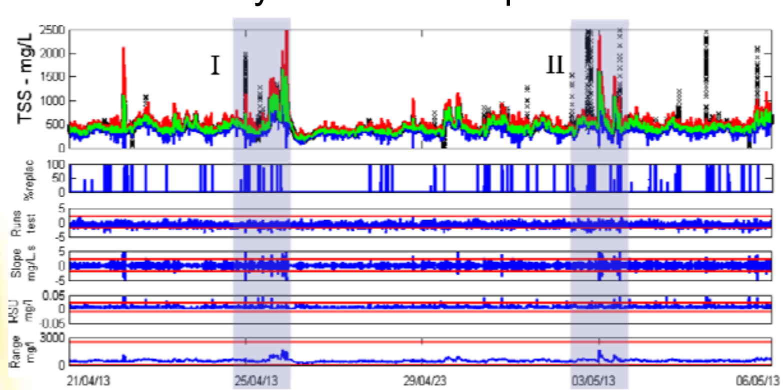
Results

- Univariate analysis – An example



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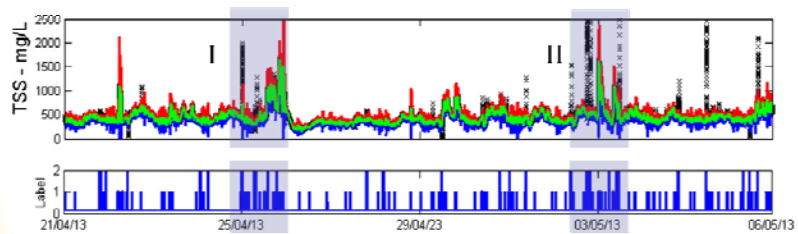
Results

- Univariate analysis – An example



About 8% of data is considered as doubtful or not valid
(typically between 5 and 50% data loss)

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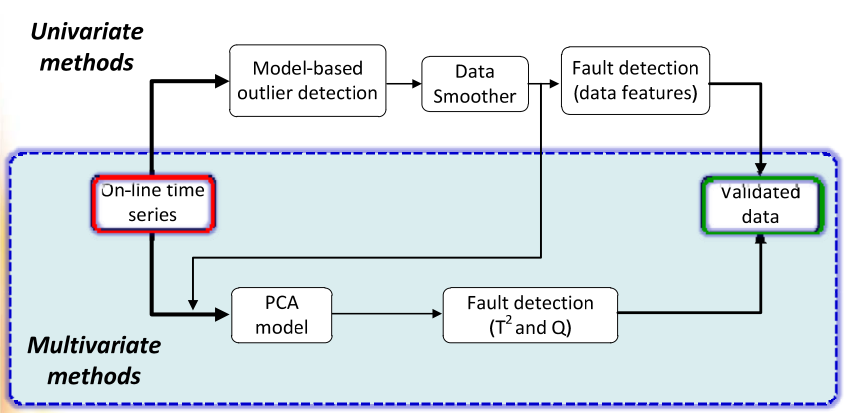
Data quality assessment - II



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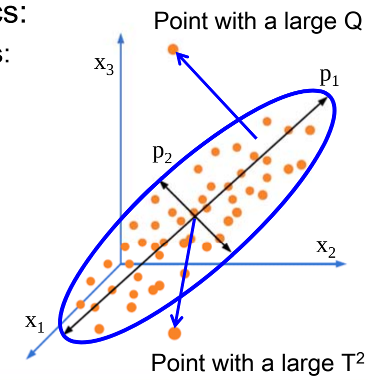
Data quality assessment - II

- Principle Component Analysis
  - Fault detection with statistics:
    - T^2: normalized sum of scores: variations within the model
    - Q: sum of squared residuals: goodness of fit of samples to the model
    - Fault detection limits are defined on the basis of “normal data”



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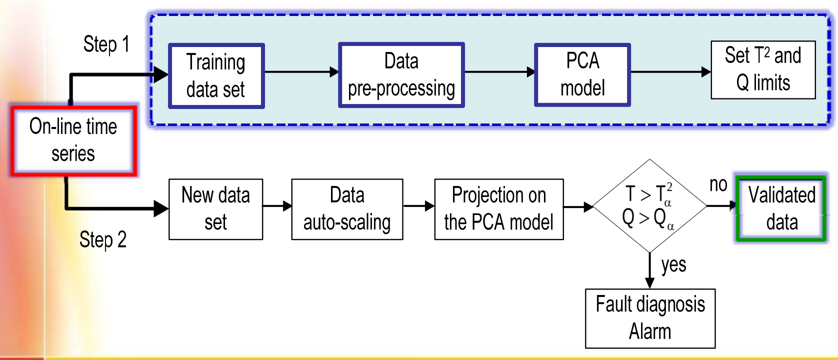
Data quality assessment - II

- Multivariate methods



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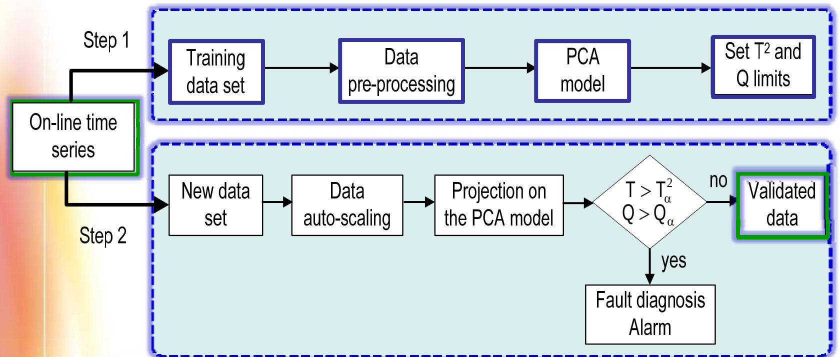

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Data quality assessment - II

- Multivariate methods (WWTP, Quebec)
  - Dataset with 8 variables (redundant, 1 w/ air clean)
    - pH_1, pH_2, $Cond_1$, $Cond_2$, $Turb_1$, $Turb_2$, $Temp_1$, $Temp_2$
  - Training: 3-day data set to build the model

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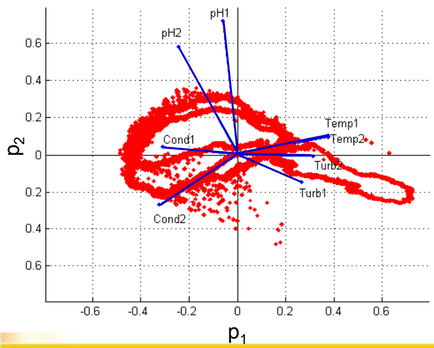
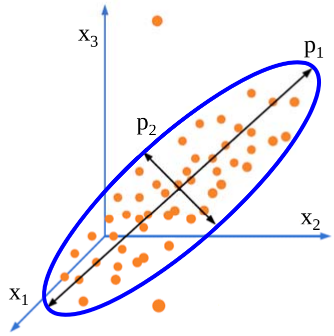
Data quality assessment - II

- Multivariate methods (WWTP, Quebec)

Data in the new PCA space – first 2 components





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79

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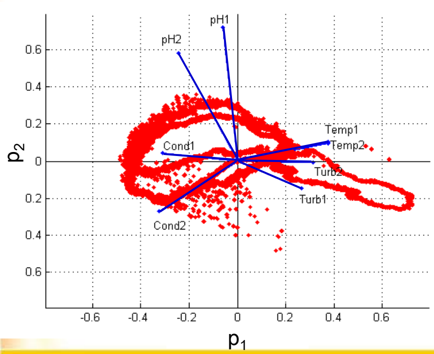
Data quality assessment - II

- Multivariate methods (WWTP, Quebec)

Data in the new PCA space – first 2 components



- Vectors represent variables and contributions to p_1 and p_2
- Each point corresponds to a sample in the new space
- Divergences between vectors represent bias between redundant sensors

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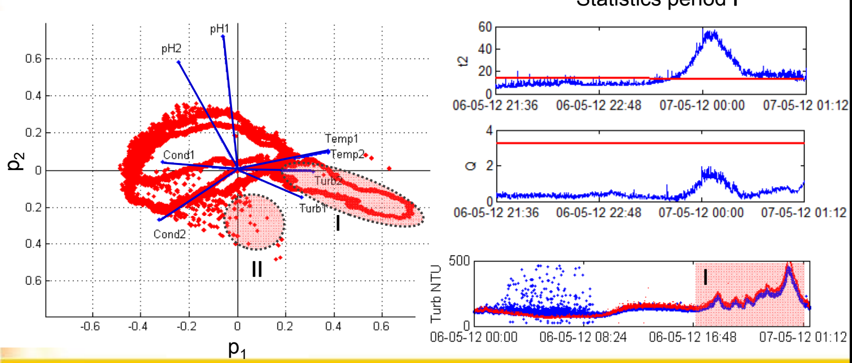
Data quality assessment - II

- Multivariate methods (WWTP, Quebec)

Data in the new space

Statistics period I



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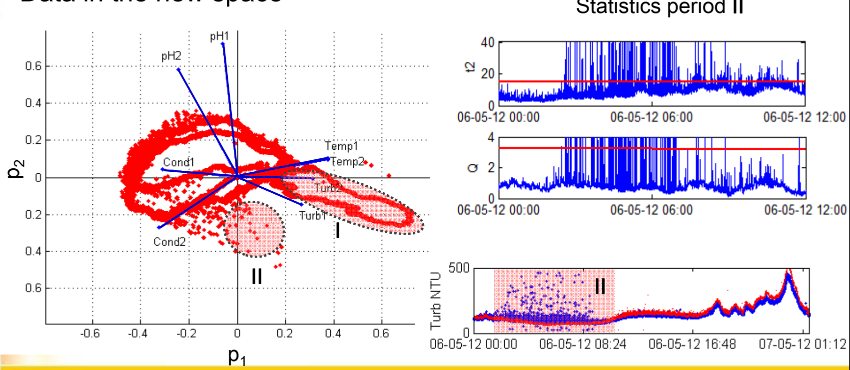
Data quality assessment - II

- Multivariate methods (WWTP, Quebec)

Data in the new space

Statistics period II



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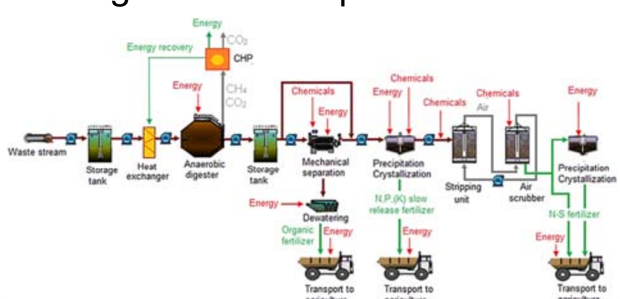
Overview

- WRRF's – the new control objectives
- The control loop
  - Control
  - Sensors
  - Actuators
  - Models and control
- Data quality
- Conclusions

Conclusions

- Our requirements become more severe
- Our ambition is reaching higher levels
- Our systems get more complicated



Conclusions

- Our set of sensors is a bit more numerous
- Our set of actuators expands a bit

- We have more of them
- We use them better

Conclusions

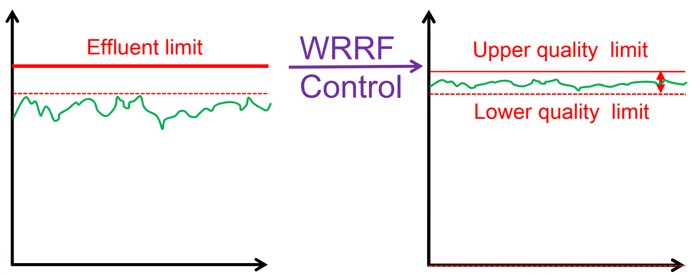
- We use them better:
  - Better installation
  - Better sensor self-diagnosis
  - Better automatic cleaning systems

  - Automatic fault detection
  - We do more maintenance work

  - Improved process knowledge (models)
  - Better controller set-up (structure, tuning)

Conclusions

- We're getting ready for the paradigm shift:



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Acknowledgments

Canada Research Chair in Water Quality Modeling

Primodal
Earth Essential Technologies

BIONEST
Wastewater Treatment Solutions™

Waterschap De Dommel

Fondation canadienne pour l'innovation
Canada Foundation for Innovation

DTU

Aalborg Universitet

københavns E

DHI
WATER • ENVIRONMENT • HEALTH

Spildevandscenter Avedøre

PH-CONSULT

KRÜGER

Lynettefællesskabet I/S

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