UNIVERSITEIT GENT

BIOMATH
Department of Applied Mathematics, Biometrics and Process Control

Economic and robustness measures as control benchmark performance criteria

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Outline of the presentation

- Benchmark performance evaluation: Problem statement
- Case study: Benchmarked control strategies
- Multi-criteria analysis
  – Grey-scale "picture"
  – Operating Cost Index
- Robustness index

Benchmark performance evaluation

- Evaluation of control strategy for three types of influent conditions
  – Collect relevant data for 7 days at 15' intervals (600 kB)
- summarized in
  – effluent quality index
  – operating cost characteristics
  – effluent constraints violations
  – average effluent concentrations
  – measures for behaviour controlled and manipulated variables

The problem: Data drowning...

Process Summary	dry	rain	storm	
EQ index =	1718.80	2483.45	2134.83	kg/d
Total Sludge Prod (disposal) =	17139	16591	18307	kg SS
Avg Sludge Prod (disposal) =	2448	2370	2615	kg SS/d
Total Sudge Prod (effluent) =	1646	2696	2216	kg SS
Avg Sludge Prod (effluent) =	235	385	317	kg SS/d
Total Sludge Prod (total) =	18785	19287	20523	kg SS
Avg Sludge Prod (total) =	2684	2755	2932	kg SS/d
AE =	12175.06	12175.06	12156.71	kWh/d
PE =	424	424	424	kWh/d
BOD (constraint limit) =	25	25	25	g/m3
% of time plant in violation (BOD) =	0.00%	0.00%	0.00%	
# of violations (BOD) =	0	0	0	
COD (constraint limit) =	125	125	125	g/m3
% of time plant in violation (COD) =	0.00%	0.00%	0.00%	
# of violations (COD) =	0	0	0	
SS (constraint limit) =	30	30	30	g/m3
% of time plant in violation (SS) =	0.00%	0.00%	0.61%	
# of violations (SS) =	0	0	2	
N (constraint limit) =	18	18	18	g/m3
% of time plant in violation (N) =	100.00%	94.25%	95.58%	
# of violations (N) =	0.01042	2.01043	2.01043	
NH4 (constraint limit) =	1	1	1	g/m3
% of time plant in violation (NH4) =	13.42%	14.63%	21.50%	
# of violations (NH4) =	5	5	7	

and more...

Composite Summary	dry			rain			storm		
	mean	st. dev.	max	mean	st.dev.	max	mean	st.dev.	max
Concentration									
TSS =	13.01	5.50	17.69	16.17	12.07	25.65	15.26	14.36	30.61
TKN =	2.24	1.07	4.98	2.86	2.61	8.69	2.69	2.29	5.62
Ntot =	36.21	10.23	39.15	28.47	10.25	39.19	32.27	15.11	39.00
NH4 =	0.42	0.68	3.03	0.68	1.53	5.75	0.60	0.88	3.03
NO =	33.97	9.40	37.34	25.61	8.65	37.37	29.58	13.39	37.16
COD =	47.95	16.07	54.14	45.11	22.86	64.35	47.33	30.82	71.48
BOD =	2.70	1.11	3.56	3.37	2.48	5.12	3.13	2.89	6.16
Load									
TSS =	235.05	99.44	558.12	384.63	287.30	1325.43	315.81	297.21	1824.91
TKN =	40.52	19.28	101.80	68.11	62.02	373.26	55.72	47.46	334.75
Ntot =	654.28	184.88	1164.20	677.39	243.89	1853.89	667.94	312.79	2185.84
NH4 =	7.57	12.28	60.63	16.08	36.49	246.95	12.39	18.30	121.41
NO =	613.76	169.82	1095.19	609.28	205.70	1700.02	612.22	277.13	1958.41
COD =	866.48	290.43	1707.61	1073.29	543.93	3329.29	979.60	637.84	4261.16
BOD =	48.72	20.06	112.35	80.28	59.06	264.01	64.74	59.87	367.29

Which criteria to use for evaluation?

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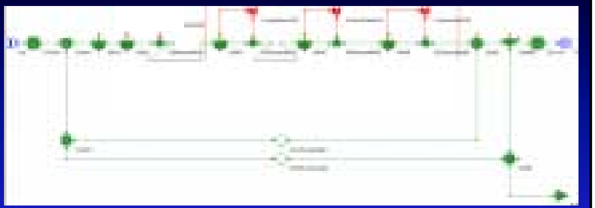
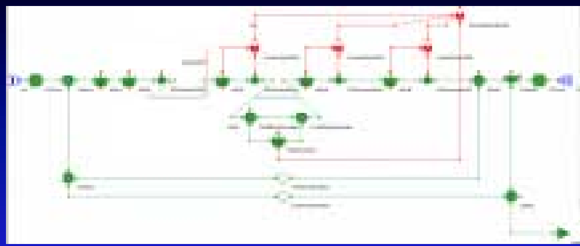
3 DO controller



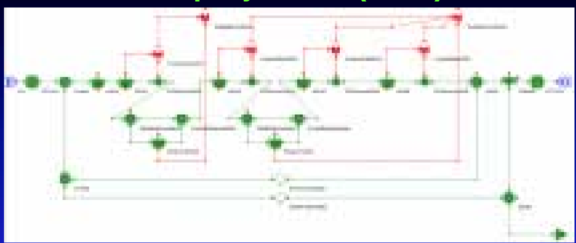
- Investments:
  - 3 DO electrodes + 3 PI controllers
  - Aeration intensity manipulation

Surmacz et al. (1996)



- Extra investments:
  - Mixing equipment
  - Respirometer after first aerated tank + cascade DO

Klapwijk et al. (1998)



- Extra investments:
  - 4th DO sensor + 4th PI controller
  - Aeration intensity manipulation
  - 2nd respirometer after anoxic tank + 2nd cascade DO

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Multicriteria analysis: grey-scale picture

- Grey-scale representation (Copp, 1999)

	Benchmark	3 DO Control	Surmacz	Surmacz / Klapwijk
Effl. Qual.	6945	6854	6737	6710
Aeration	6359	4999	4959	4994
%Time	8.36	6.58	5.84	5.39
NO_3-N	12.26	10.80	10.03	10.08
NH_4-N	9.84	9.79	10.32	9.62

Best system (?)

!!! Conclusion depends on look-up table
- based on limited number of criteria
- for particular control strategies

Multicriteria analysis: grey-scale picture

- Omitting a control strategy changes the picture:

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versus

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!!! Grey scale approach: only relative comparison

Multicriteria analysis: Operating Cost Index

- Drawbacks Benchmark / Grey-scale :
  - Hard to communicate with other Benchmarkers
  - Difficult to relate results to practice
- Solution: Operating Cost Index
  - Criteria weighed in economic sense

$$OCI = \gamma_1 \cdot EQ + \gamma_2 \cdot (AE + PE) + \gamma_3 \cdot P_{sludge}$$

Flanders:
γ_1 = 50 Euro/EQ γ_2 = 25 Euro/kWh.d γ_3 = 75 Euro/kg TSS.d

  - Investments costs only calculated for promising strategies

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Multicriteria analysis: Operating Cost Index

Cost factor	Open loop	3DO	Surmacz	Klapwijk
EQ (kE/yr)	347	343	337	335
Sludge (kE/yr)	180	180	180	180
Pumping (kE/yr)	11	11	11	11
Aeration (kE/yr)	159	125	124	125
OCI (kE/yr)	696	658	651	650
Savings (kE/yr)	0	38	45	46

- Investing in DO-control is viable
- Investing in respirometers is not economically sound

$\Rightarrow$ 3 DO control best

$\Leftrightarrow$ Grey-scale analysis
although easier to evaluate intrinsic controller performance

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Multicriteria analysis: conclusions

- Benchmark evaluation strategy - compact measures
  - OCI: rejection of control strategies that are obviously not economically feasible
  - Grey-scale analysis of remaining strategies
  - More thorough economic analysis
- 3 DO control as Benchmark reference case
  - Better performance than open loop
  - Well accepted in practice
  - Basic control strategy as reference for more advanced ones

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Transferability of benchmark results

- Benchmarking = simulated “standard” plant
- Performance for a non-standard plant ?
  - influent composition
  - temperature
  - sludge characteristics (kinetics, stoichiometry)
- Need for ‘transferability’ criterion
  - expresses range of applicability of benchmark results
  - expresses sensitivity of benchmark results

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Robustness index

- OCI as single measure of performance
- Assess sensitivity of OCI to *p* process parameters

$$S = [S_1 S_2 \cdots S_p] \quad \text{with} \quad S_i = \frac{\partial OCI}{\partial \theta_i} \cdot \frac{\Delta\theta_i}{OCI} \quad i = 1, \cdots p$$

$\Delta\theta$: range of change one can actually expect

- Consider changes likely to affect performance
  - overall loading
  - COD and N loading
  - sludge age
  - nitrate recycle flow rate
  - temperature
  - rain conditions
  - storm conditions

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Robustness index

- Again: too many criteria !
  ==> Measure of global sensitivity:

$$SI = \sqrt{\frac{1}{p}\sum_{i=1}^{p} S_i^2}$$

- Think positive: Robustness index:

$$RI = 1 \Big/ \sqrt{\frac{1}{p}\sum_{i=1}^{p} S_i^2}$$

Robustness Index

Case study:

OCI Sensit. to:	Open loop	3DO	Surmacz	Klapwijk
Influent flow	0.123	0.141	0.152	0.150
Sludge age	0.0177	0.0138	0.0323	0.0249
NO_3 recycle	0.0115	0.0116	-0.0017	-0.000279
Temperature	0.108	0.199	0.133	0.156
RI	11.9	9.16	9.79	8.74

- Open loop is most robust !
  But: stable lowest performance

General

- Use RI for first selection
- Need for practical interpretation of RI

Discussion issues

- Problem:
  current Benchmark evaluation procedure
  - Data drowning: too many criteria
  - Transferability to practice ?
- Solution: compact evaluation criteria
  - Grey-scale analysis and Operating Cost Index
  - Robustness Index
- Case study:
  - 3DO control should become reference situation