OPPORTUNITIES IN OPTIMIZATION AND CONTROL OF WASTEWATER TREATMENT PLANTS

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Outline

- ‘Process Systems Engineering’ ?
- Optimization of **ALTERNATING AEROBIC ANOXIC** systems
- Control studies from the perspective of sludge control
- Looking into the future

Process Systems Engineering (PSE)

A combination of computer aided decision support methods in

- Modelling
- Simulation
- Applied statistics
- Design
- Optimization
- Control

for an essentially unlimited set of process; chemical, biological (*i.e.* environmental), food processing, pharmaceutical... systems

Problems that may be solved by PSE?!

- WWTPs need to be operated continuously despite large perturbations in
    - Pollution load
    - Flow

  Constraints on effluent become tighter each year
    - European Water Framework Directives
- Many plants are either controlled manually or NOT operated!
- ‘Data mining’

  Abundant exp. data need to be interpreted

NOT AN EASY TASK !!!

- Complex plants with processes of different nature (chemical, biological, mechanical)
- Complicated dynamics (time constants within a very extensive range)
- Varying objectives
- Frequently changing disturbances
- Some information essential for the operation cannot be quantified (smell, color, microbiological quality)
- Measurement problems (unreliable sensors, vague info)

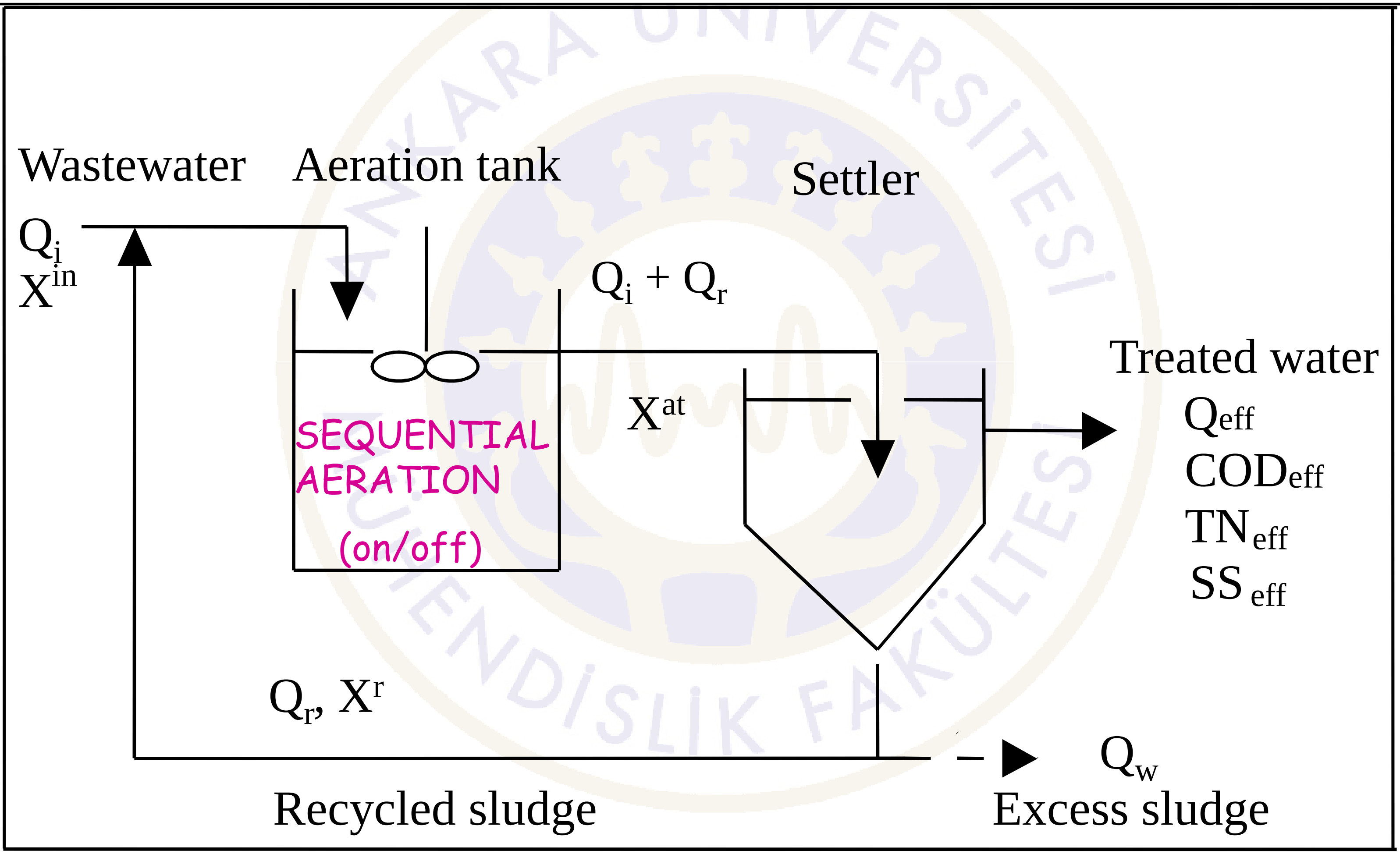
PROBLEM:

- ACHIEVE nitrification/denitrification in a conventional activated sludge system designed for C removal only

  ➔without installing new anoxic tank

  ➔at optimal operating cost

ALTERNATING AEROBIC ANOXIC SYSTEMS AND THEIR OPTIMIZATION



AAA ACTIVATED SLUDGE SYSTEM

SCOPE

- Alternating Aerobic-Anoxic (AAA) systems
  (carbon and nitrogen removal)
- Main operational cost is due to
  energy used by the aeration equipment
  (operated consecutively as nonaerated/aerated manner)
- Energy optimization is sought
  by minimizing the
  aerated fraction of total operation time

- *A non-trivial dynamic optimization problem*

STEPS OF THE STUDY

- Selection of
  - **Activated sludge model** (ASM-3)
  - **Settler model** (Vitasovic, 10 layers)
    - ***Settling velocity model*** *(Takacs)*
- Mass balances; a general dynamic model for activated sludge system
- Simulation for start-up period
- Optimal aeration profile for normal operation period

ACTIVATED SLUDGE MODEL No. 3

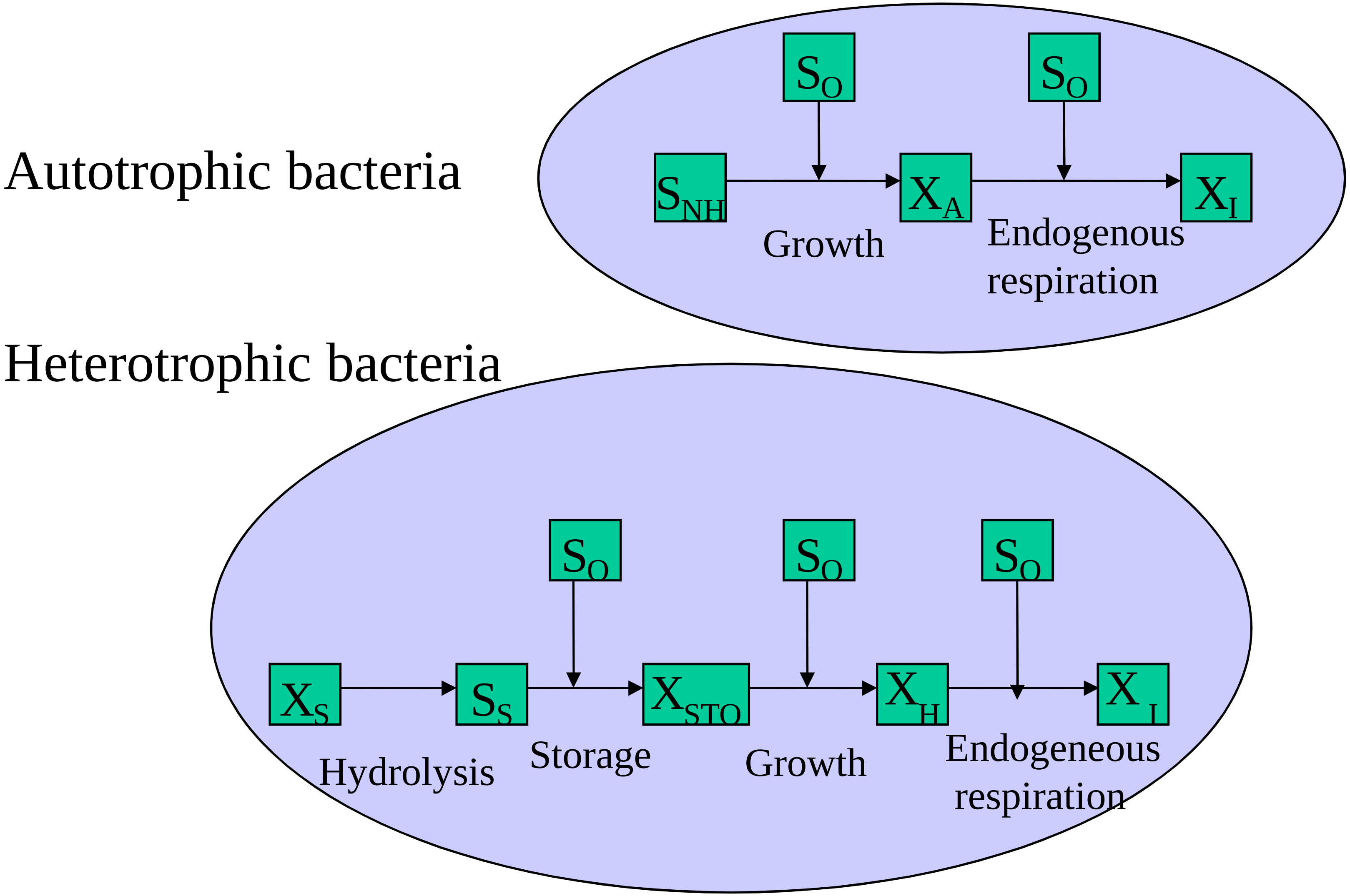
(Gujer *et al.* 1999)

Correction for defects in ASM No.1

- ☑ Storage of readily biodegradable substrate
- ☑ Less dominating importance of hydrolysis
- ☑ Separation of conversion processes for heterotrophs and autotrophs in aerobic and anoxic state
- ☑ Alkalinity correction in nitrification rate

- 13 components (soluble and particulate)
- 12 processes

ASM-3 CONVERSION PROCESSES



Autotrophic bacteria

Heterotrophic bacteria

ASM-3 Soluble Components (S)

S_O : Dissolved oxygen

S_I : Soluble inert organics

S_S : Readily biodegradable organic substrates

S_{NH} : Ammonium and ammonia nitr.

S_{N2} : Dinitrogen

S_{NO} : Nitrate & nitrite nitrogen

S_{HCO} : Alkalinity of wastewater

ASM-3 Particulate Components (X)

X_I : Inert particulate organic material

X_S : Slowly biodegradable substrates

X_H : Heterotrophic biomass

X_{STO} : Organics stored by heterotrophs

X_A : Nitrifiying autotrophic biomass

X_{TS} : Total suspended solids

MASS BALANCES AROUND ACTIVATED SLUDGE SYSTEM

For non-aerated periods :

$$\frac{dX_i^{at}}{dt} = \frac{Q_{in} X_i^{in} + Q_{rs} X_i^{rs} - (Q_{in} + Q_{rs}) X_i^{at}}{V_{at}} + R_i$$

i: components of ASM-3 X_i^{rs} from settling model

For aerated periods (dissolved oxygen incorporated):

$$\frac{dX_i^{at}}{dt} = \frac{Q_{in} X_i^{in} + Q_{rs} X_i^{rs} - (Q_{in} + Q_{rs}) X_i^{at}}{V_{at}} + R_i + k_L a (S_O^{sat} - S_O^{at})$$

STATE VARIABLES

73 dimensional vector

- 13 ➔ Concentrations of ASM-3 components in aeration tank

  7 solubles

  6 particulates

- 60 ➔ Concentrations of particulate components of ASM3 for each layer in settler

START-UP SIMULATION

- With assumed constant aeration profile

  (0.9 hrs non-aerated / 1.8 hrs aerated)

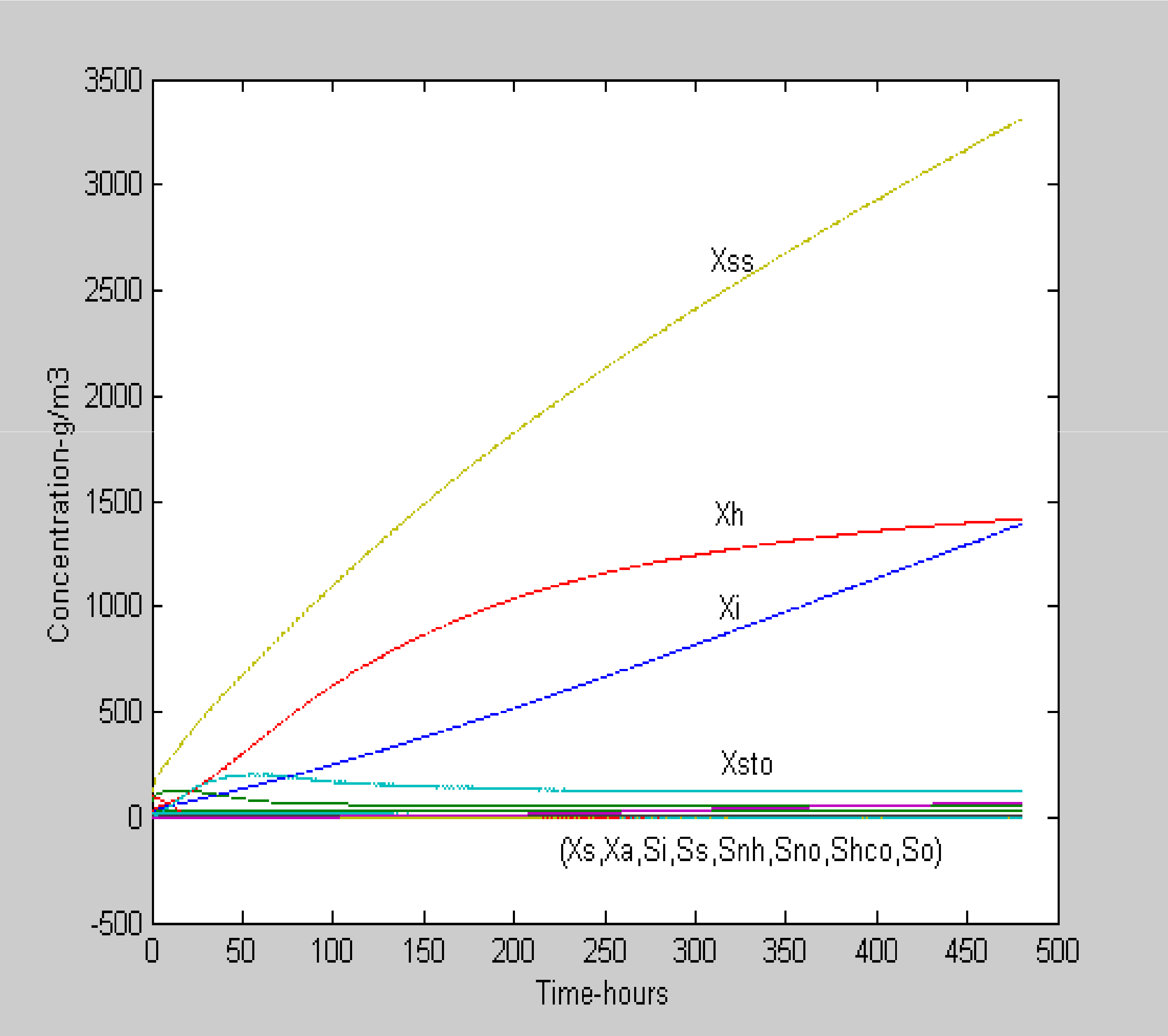
  for 20 days $k_L a$: 4.5 h^{-1}

➔ Increase microorganism concentration

➔ Improve settling

➔ Determine initial values of state variables

ASM-3 variables during start-up



Suspended solids

Heterotrophic organ.

Inert. part. org. mat.

Cell int. storage products

OPTIMIZATION PROBLEM

min $$J = \sum_{k=1}^{M} b^k / \sum_{k=1}^{M} (a^k + b^k)$$

s.t. mass balance equations

$$\frac{dX}{dt} = f^{(1)}(X)$$ nonaerated periods

$$\frac{dX}{dt} = f^{(2)}(X)$$ aerated periods

Soft constraints

HARD CONSTRAINTS

- Min. and max. lengths of non-aeration and aeration periods
- Treated water discharge standards
- Total operation time
- Dissolved oxygen concentration

EVOLUTIONARY ALGORITHM (EA)

- Darwin’s natural selection principle
  - Genes: durations for non-aerated / aerated periods
  - Chromosome (individual) : an aeration profile
  - Population: pool of aeration profiles
- Start from an initial population
- Evaluate ‘fitness value’
- Create a new generation

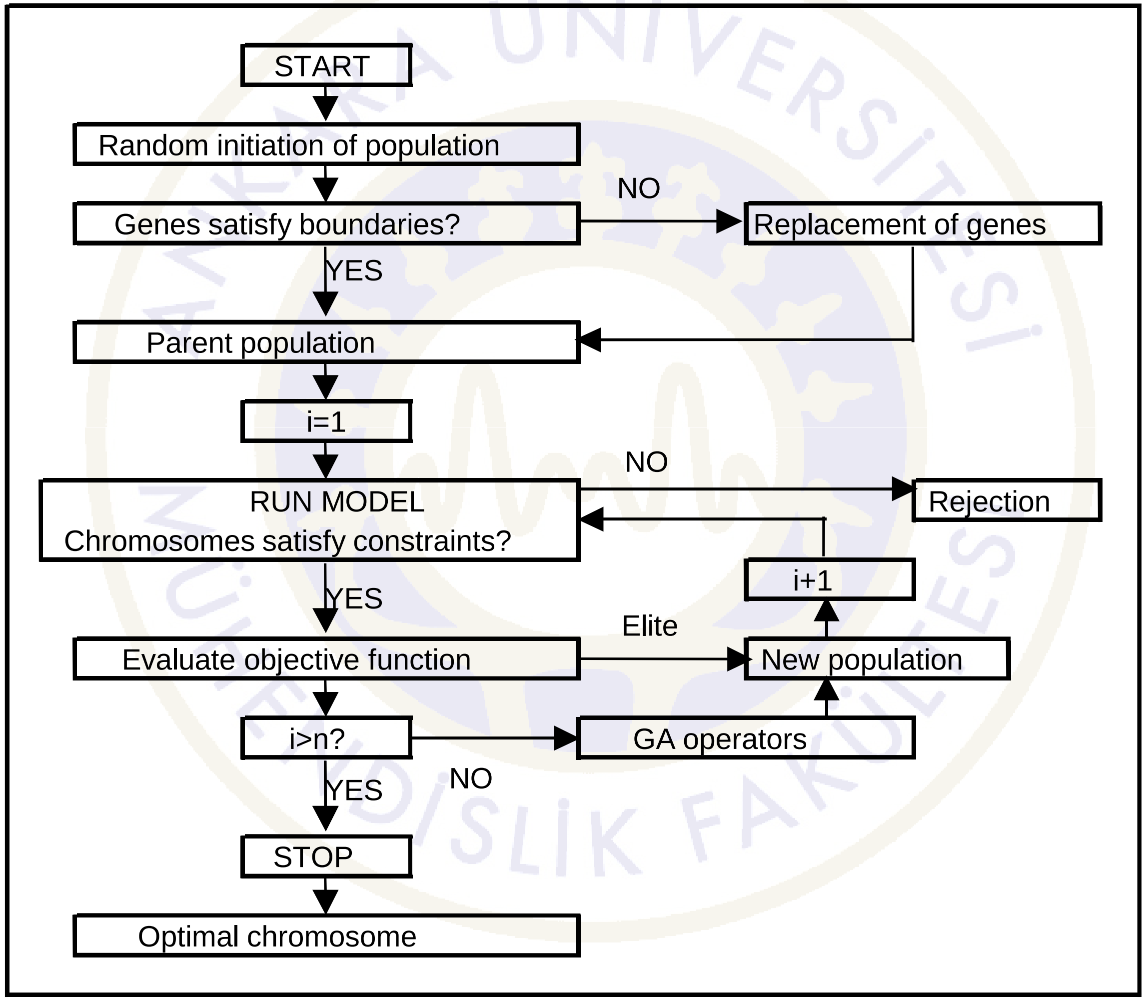
GENETIC OPERATORS

- SELECTION *(ranking and roulette wheel)*
- CROSS-OVER *(mixing two individuals)*
- MUTATION *(creating a new individual)*
- ELITISM *(adding the best parent individual to the new population)*

CONSTRAINTS HANDLING METHODS

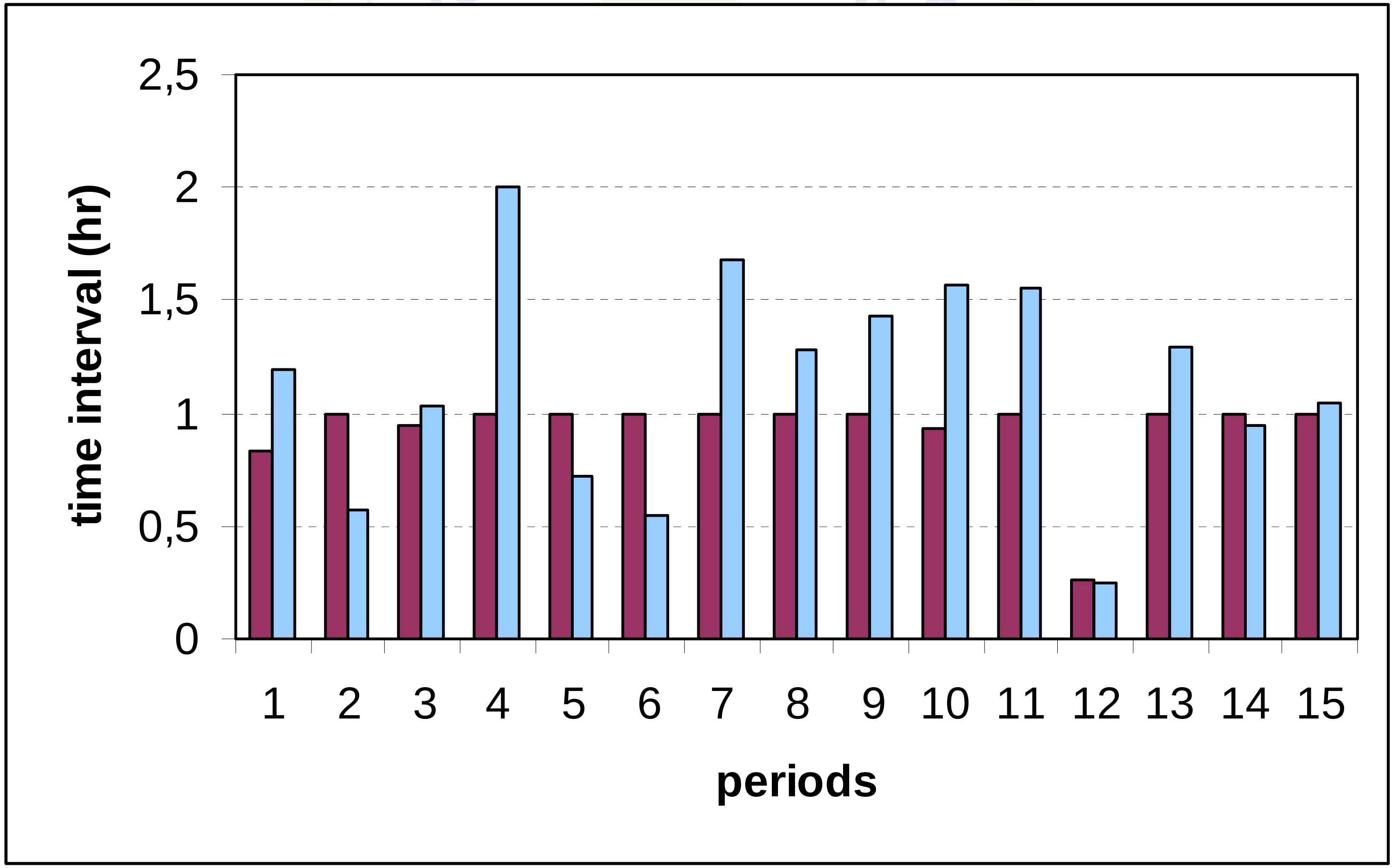
- Rejection of infeasible individuals
- Penalizing infeasible individuals

EVOLUTIONARY ALGORITHM
Rejection of Infeasibles



Optimal aeration profile

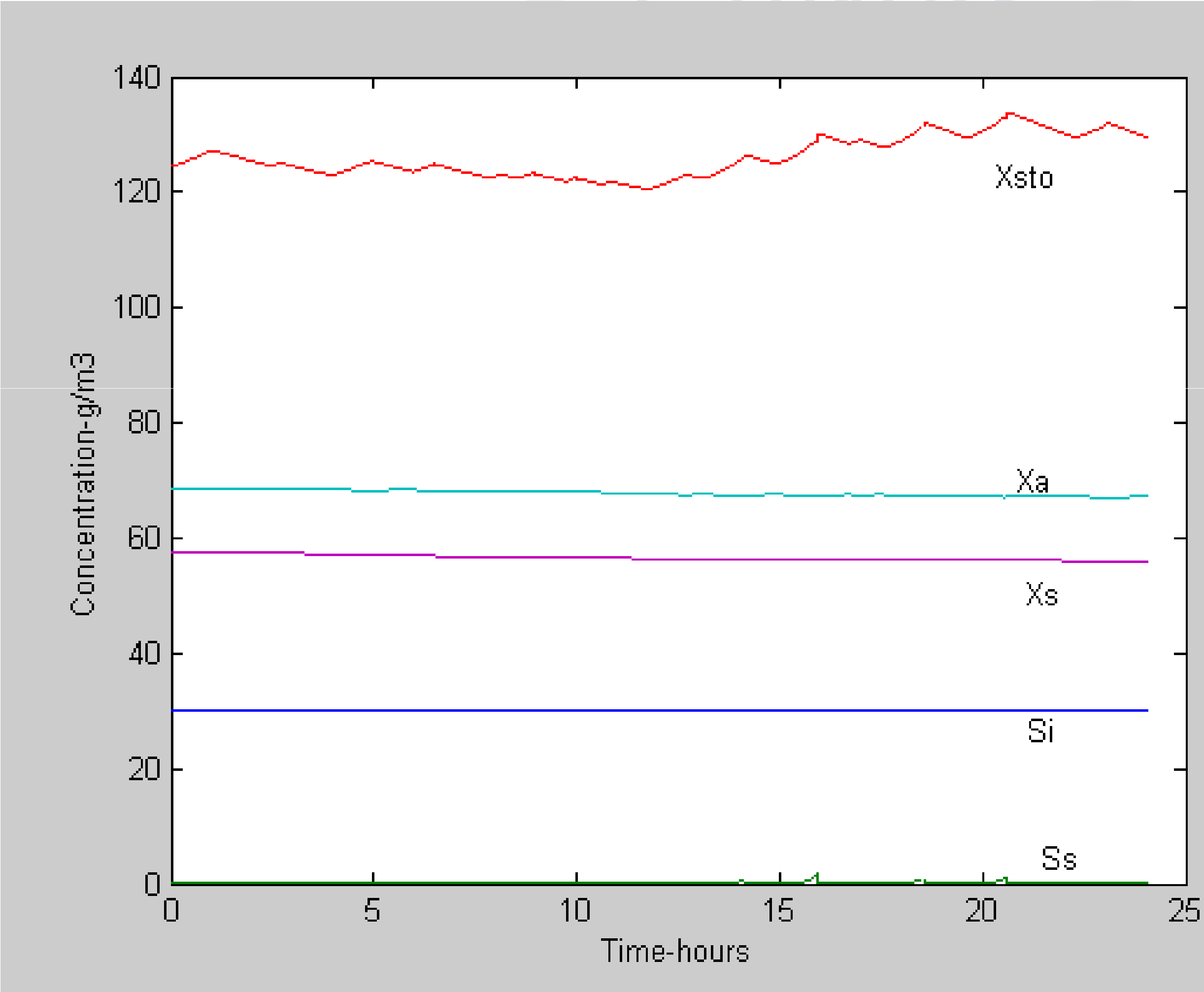
(REJECTION)



Comparison of Algorithms

Constraint handling algorithm	**Rejection of infeasibles**	**Penalizing infeasibles**
Treatment	Proper	Proper
Objective function (%)	55.04	58.07
Energy savings (relative %)	17.44	12.90
CPU time (hours)	68.00	65.36

ASM3 Components in Aeration Tank by optimal aeration profile



Cell internal storage product of heterotrophic organisms

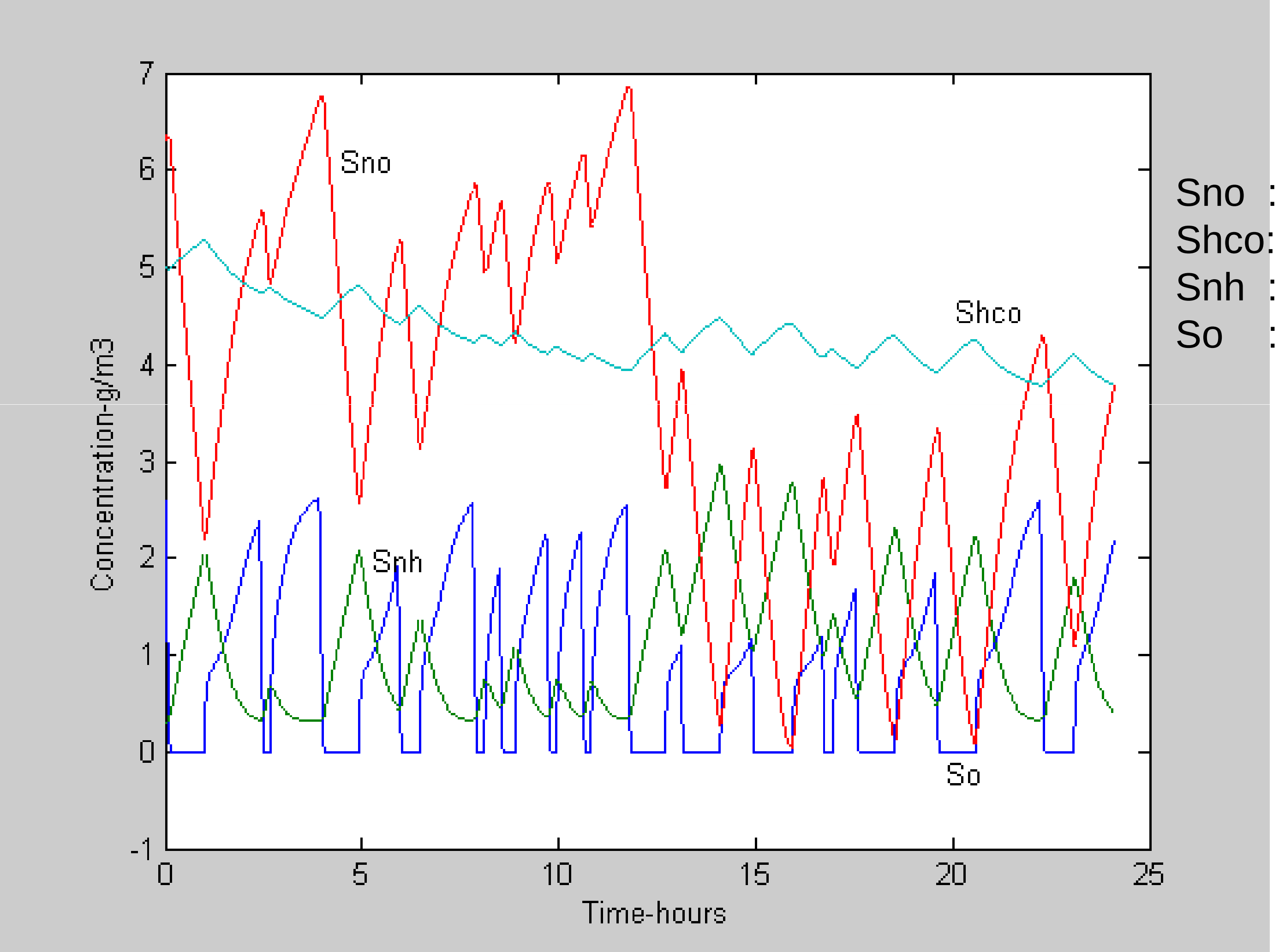
Nitrifiying autotrophic organisms

Slowly biodegradable substrates

Inert soluble organic material

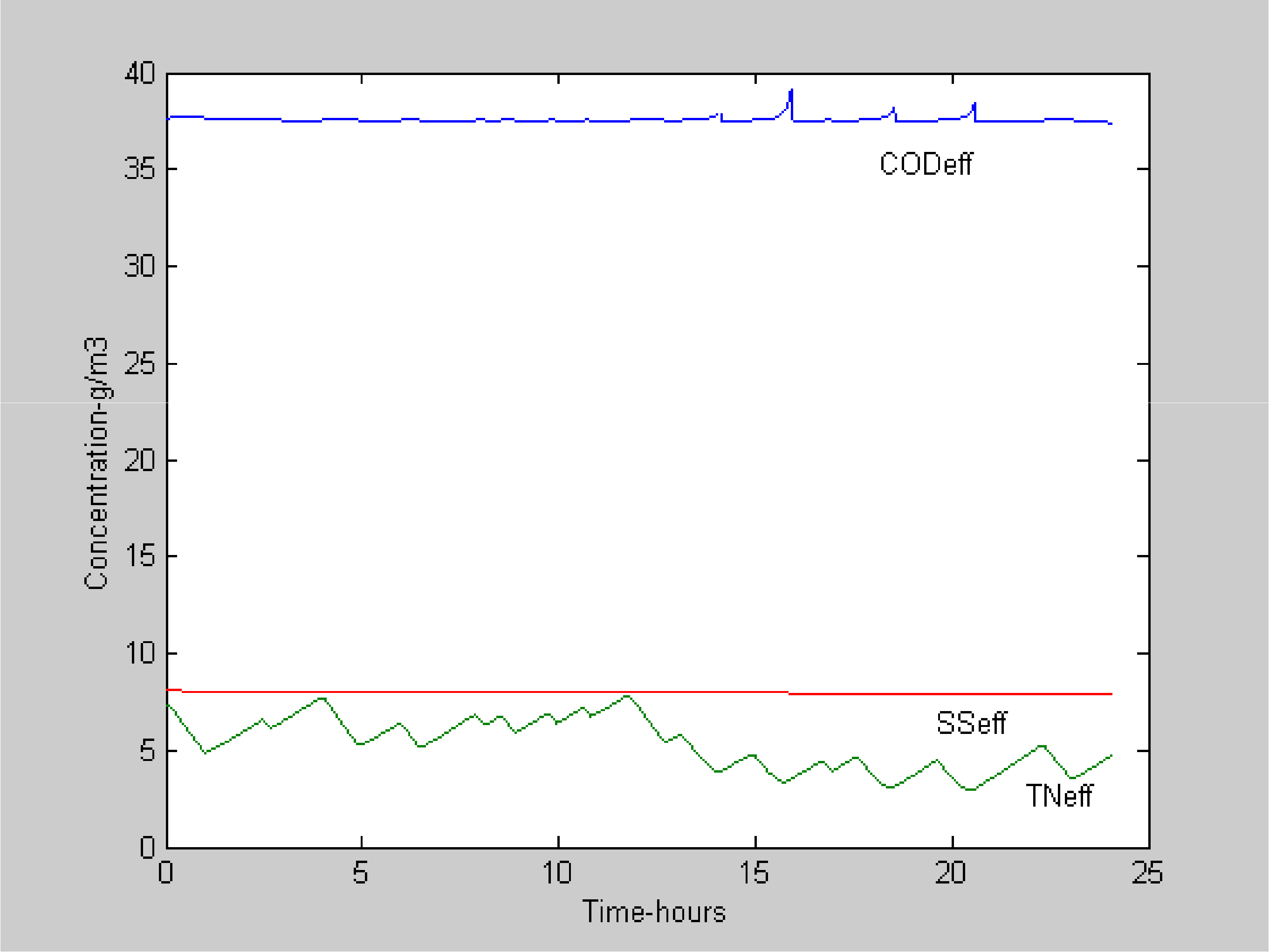
Readily biodegradable organic substrates

Operation results by optimal aeration profile _1



Sno : NO2 & NO3 N
Shco: alkalinity
Snh : ammonia nitrogen
So : dissolved oxygen

Operation results by optimal aeration profile _2



TREATMENT PERFORMANCE

Objective function : 58.0 %

Energy savings : 12.90 %

Treatment parameters (g/m^3)	Inlet flow	Effluent (24 hours)	Discharge standards
COD	260	37.42	125
Total nitrogen	25	4.82	10
Total suspended solids	125	7.91	30

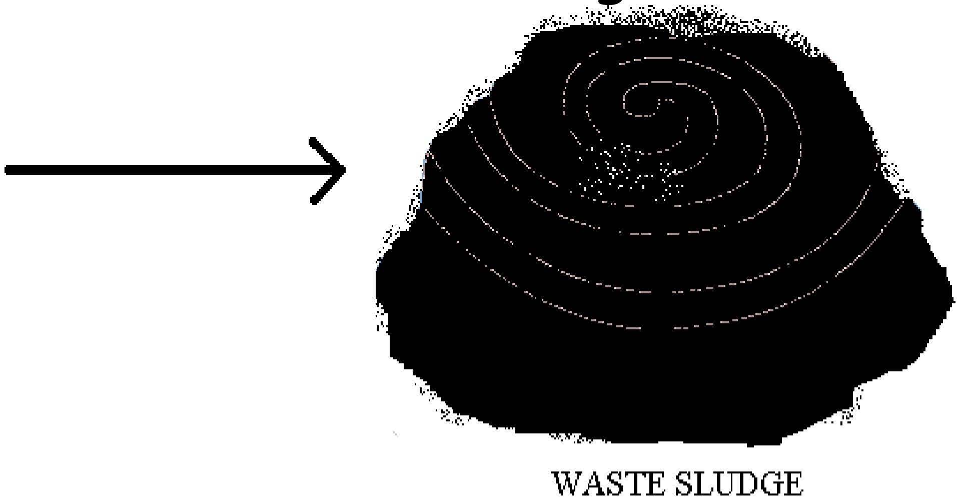
OVERALL EVALUATION

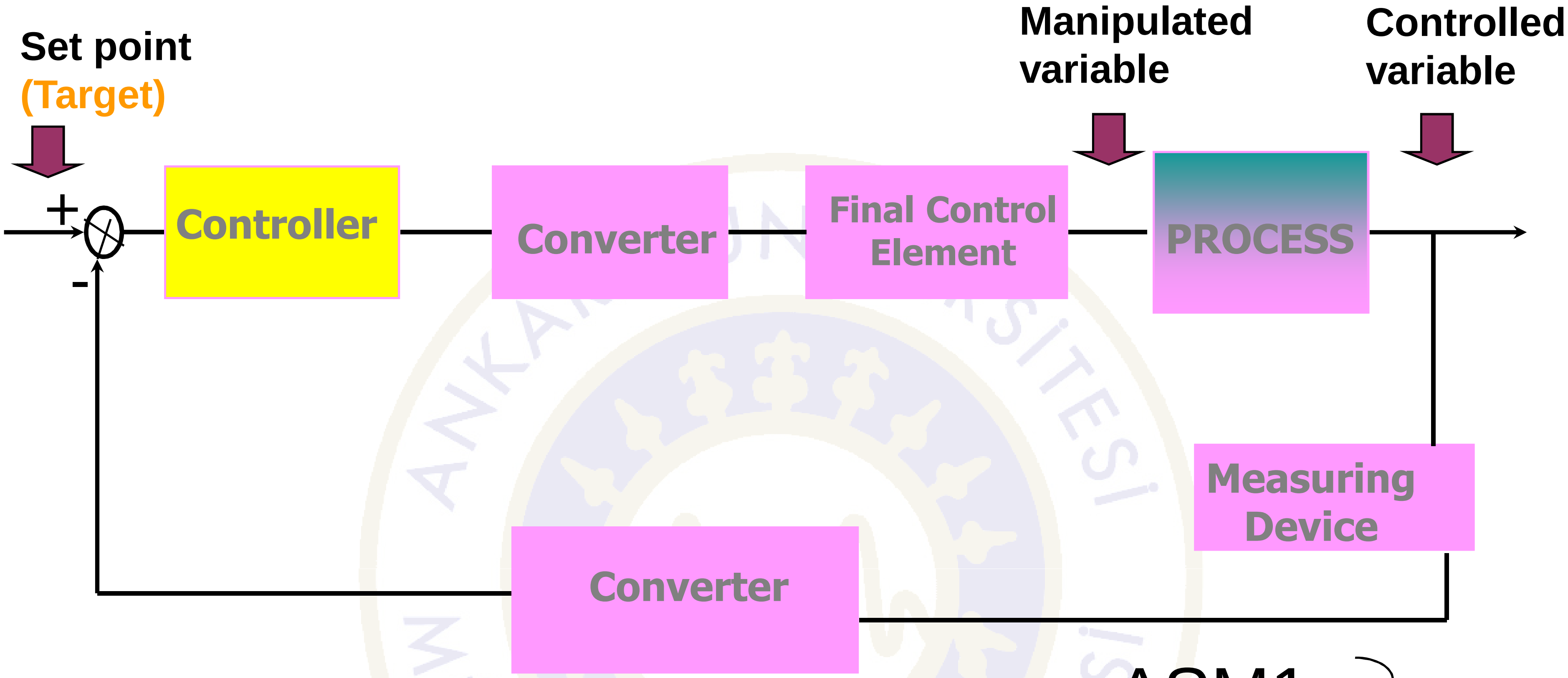
… holds promise for

- Nitrogen removal with no additional investment cost in existing plants
- Easy design and low investment cost for new plants
- Easy operation, and energy savings

Yet, another important problem, among others…

Mountains of accumulating sludge …





Set point
(Target)

Manipulated variable

Controlled variable

+

-

Controller

Converter

Final Control Element

PROCESS

Measuring Device

Converter

MODELLING

...the first step

- ASM1
- ASM2d
- ASM3
- COST Benchmark
- …

IWA Task group

- Dissolved oxygen conc.
- Ammonia & nitrate conc.
- MLSS concentration
- Δ (BOD)

Controlled variables

Manipulated variables

- Aeration rate
- Dilution rate
- Internal recycle flow rate
- Sludge recycle rate
- External carbon dosing

This problem,
recently unveiled by stricter regulations,
can be tackled by a CARBON-BASED MODEL

ASM3c

where

organic state variables are expresses in terms of organic C.

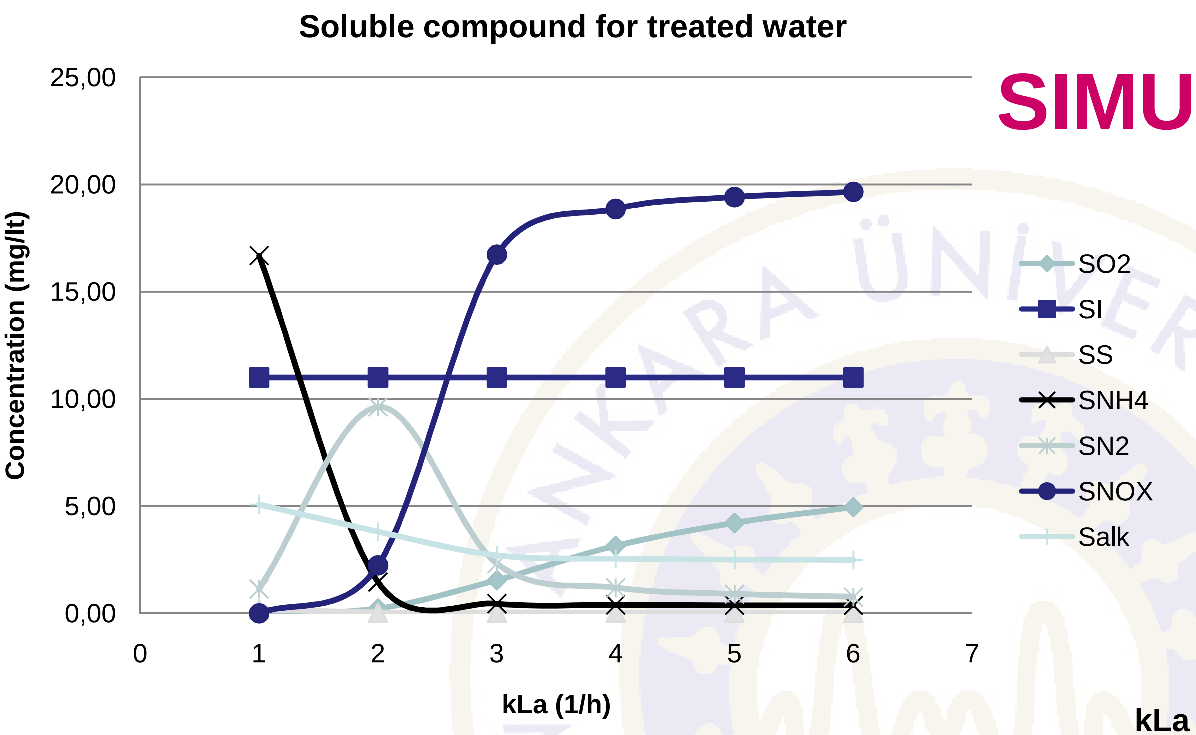
Stoichiometric matrix

	Compound i →	1	2	3	4	5	6	7	8	9	10	11	12	13
Process	j	SO2	SI	SS	SNH4	SN2	SNOX	SALK	XI	XS	XH	XSTO	XA	XSS
	Expressed as→	[O2]	[TOC]	[TOC]	[N]	[N]	[N]	[Mole]	[TOC]	[TOC]	[TOC]	[TOC]	[TOC]	[SS]
1	Hydrolysis		fsi	x1	y1			z1		-1				-Ixs
	Heterotrophic organisms													
2	Aerobic storage of SS	x2		-1	y2			z2				YSTO,O2		t2
3	Anoxic storage of SS			-1	y3	-x3	x3	z3				YSTO,NOX		t3
4	Aerobic growth of XH	x4			y4			z4			1	-1/YH,O2		t4
5	Anoxic growth (denitrific.)				y5	-x5	x5	z5			1	-1/YH,NOX		t5
6	Aerobic endog. respiration	x6			y6			z6	f1		-1			t6
7	Anoxic endog. respiration				y7	-x7	x7	z7	f1		-1			t7
8	Aerobic respiration of XSTO	x8										-1		t8
9	Anoxic respiration of XSTO					-x9	x9	z9				-1		t9
	Autotrophic organism													
10	Aerobic growth of XA	x10			y10		1/YA	z10					1	t10
11	Aerobic endog. respiration	x11			y11			z11	f1				-1	t11
12	Anoxic endog. respiration				y12	-x12	x12	z12	f1				-1	t12

Composition matrix

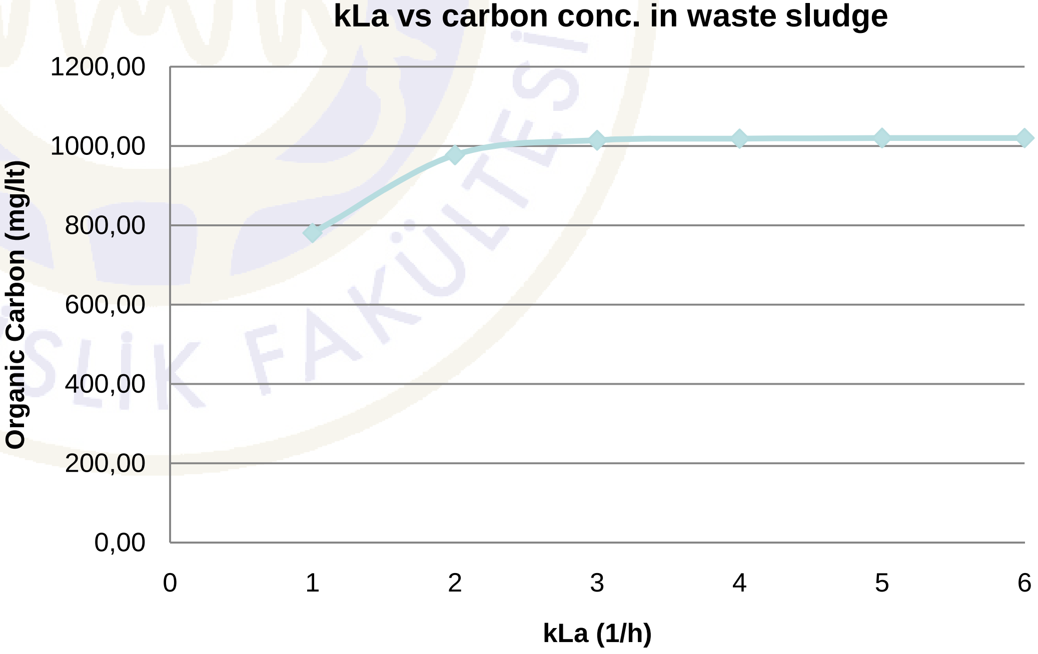
k	Conservatives	ik,l	SO2	SI	SS	SNH4	SN2	SNOX	SALK	XI	XS	XH	XSTO	XA	XSS
1	ThOD	gThOD	-1	Ithod,si	Ithod,ss		-1.71	-4.57		Ithod,xi	Ithod,xs	Ithod,bm	3	Ithod,bm	
2	Nitrogen	gN		in,sı	In,ss	1	1	1		In,xı	In,xs	In,bm		In,bm	
3	Ionic charge	Mole				1/14		1/14	-1						
4	SS	gSS								iss,xi	iss,xs	iss,bm	1.80	iss,bm	

RESULTS OF SIMULATION STUDIES

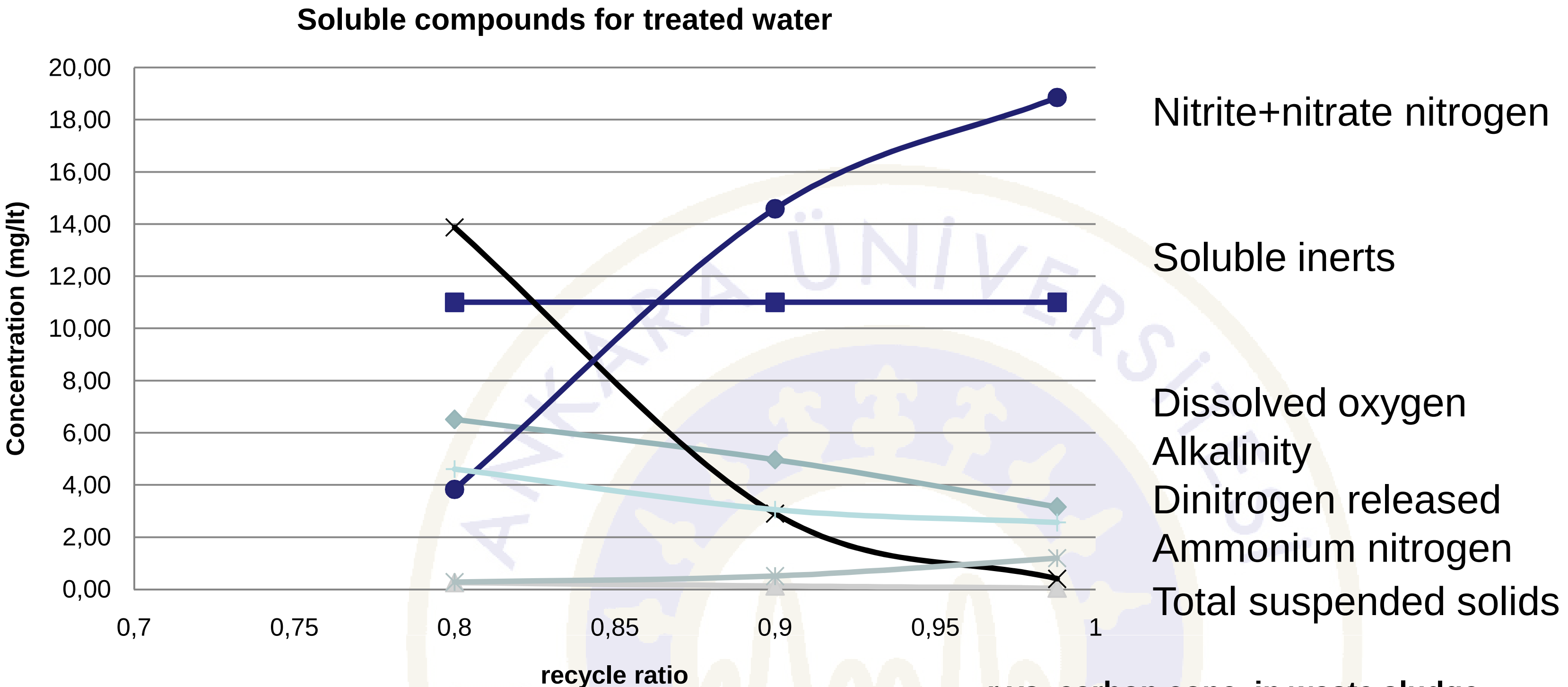


Dissolved oxygen
Soluble inerts
Total suspended solids
Ammonium nitrogen
Dinitrogen released
Nitrite+nitrate nitrogen
Alkalinity

Effect of aeration rate

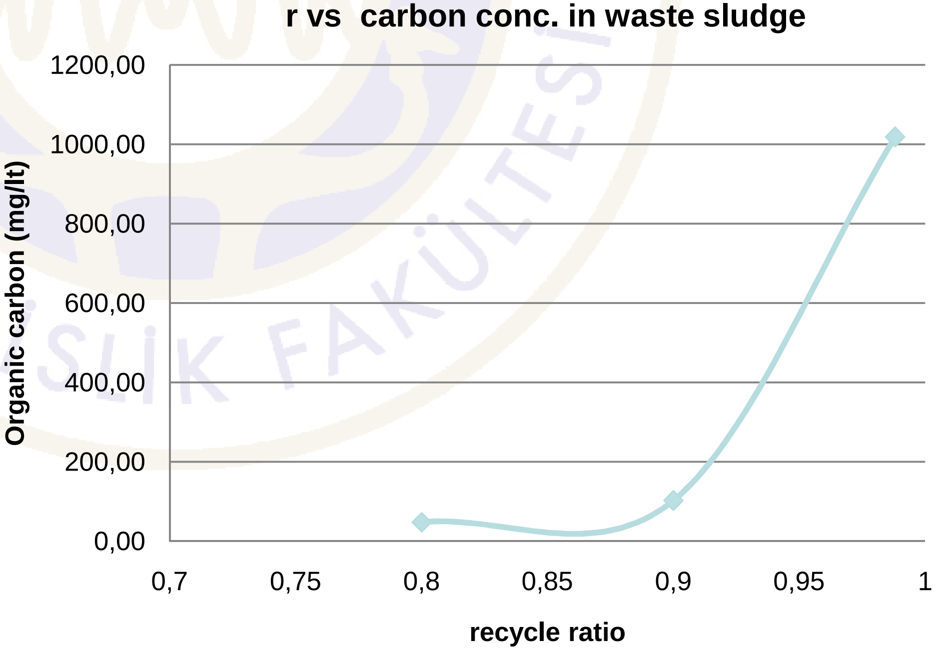


Q = 1000 m3/day, R = 0.988
Sin = 19 mg/lt



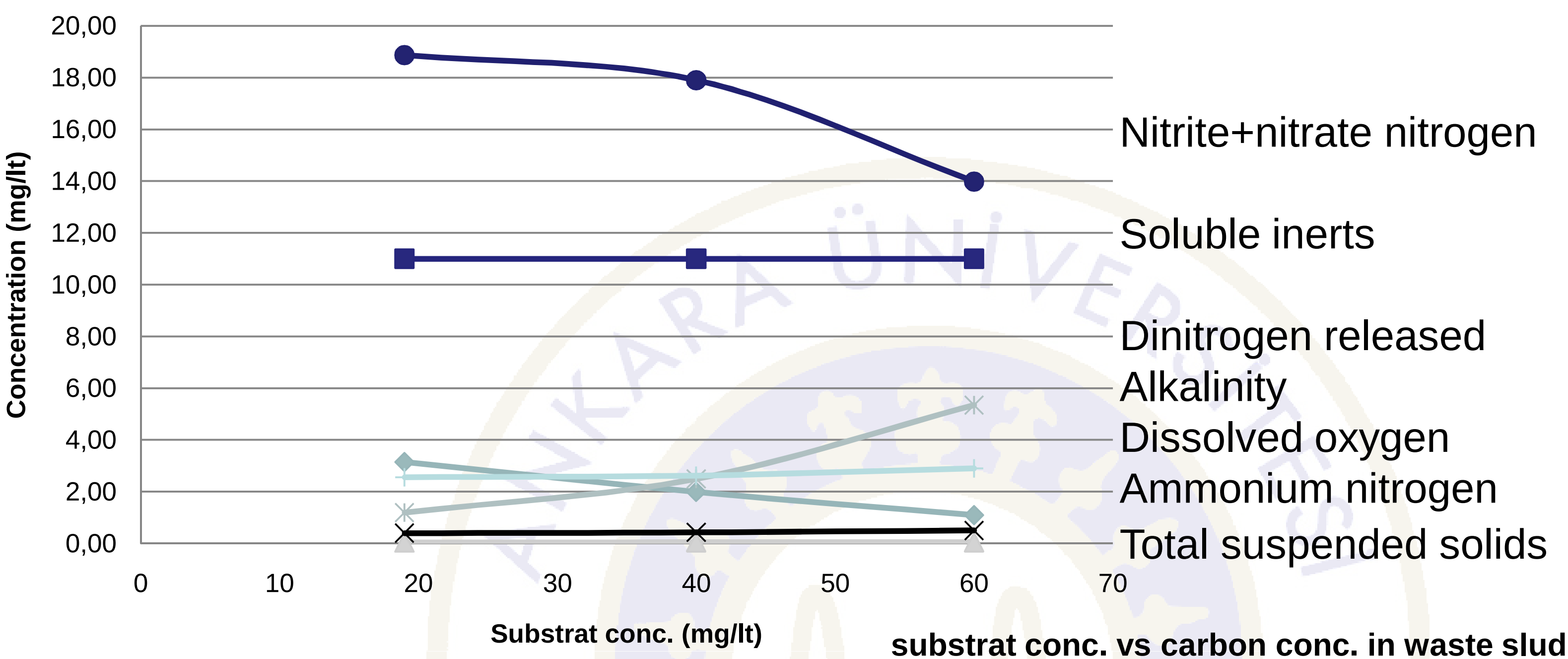
Effect of sludge recycle

R ➲ better as a
manipulated variable
for C control in sludge



kLa = 4 1/h, Sin = 19 mg/lt
Q = 1000 m3/day

Soluble compounds for treated water

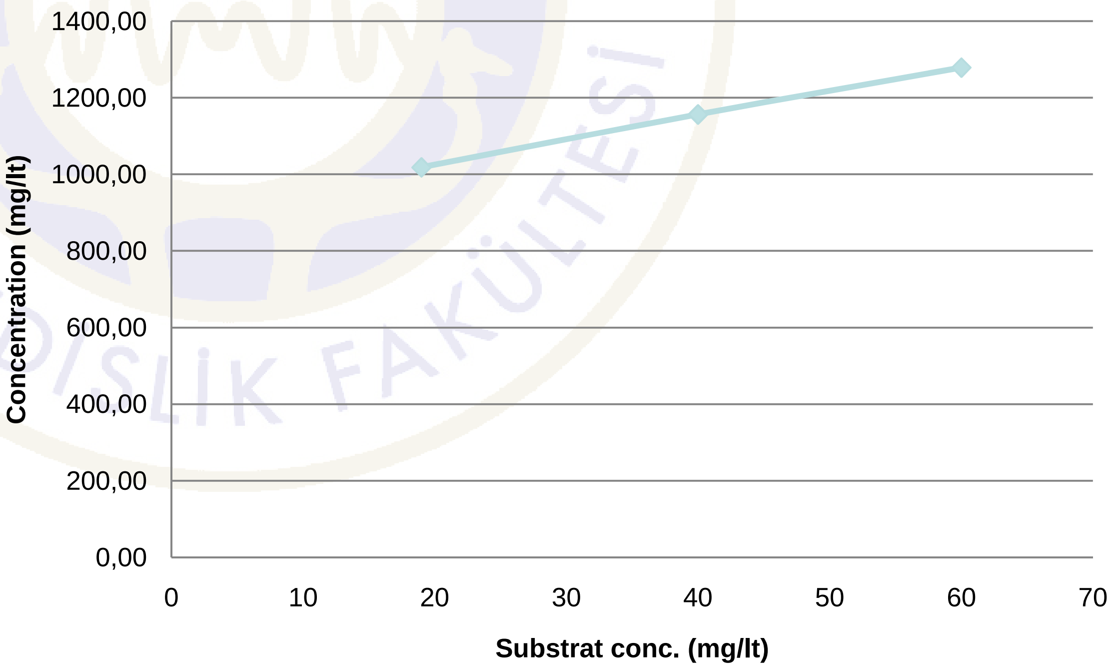


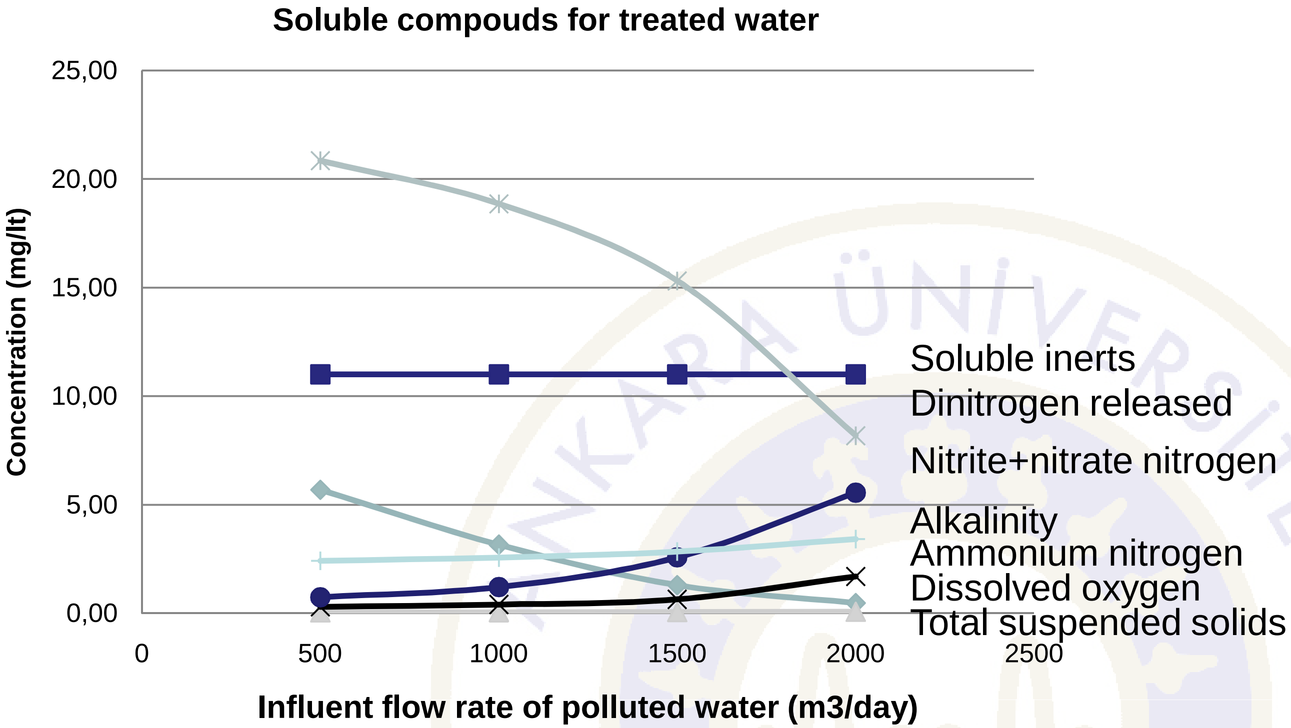
Effect of CONCENTRATION changes in incoming waste water

kLa = 4 1/h, R = 0.988

Q = 1000 m3/day

substrat conc. vs carbon conc. in waste sludge

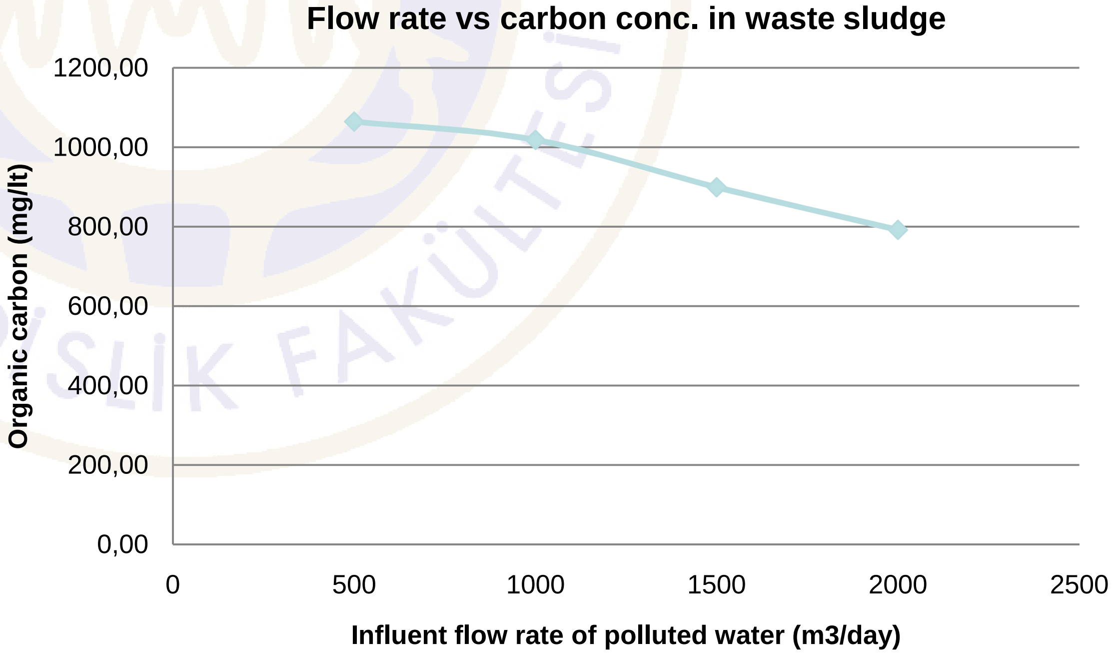




Effect of FLOW changes in incoming waste water

kLa = 4 1/h, R = 0.988

Sin = 19 mg/lt



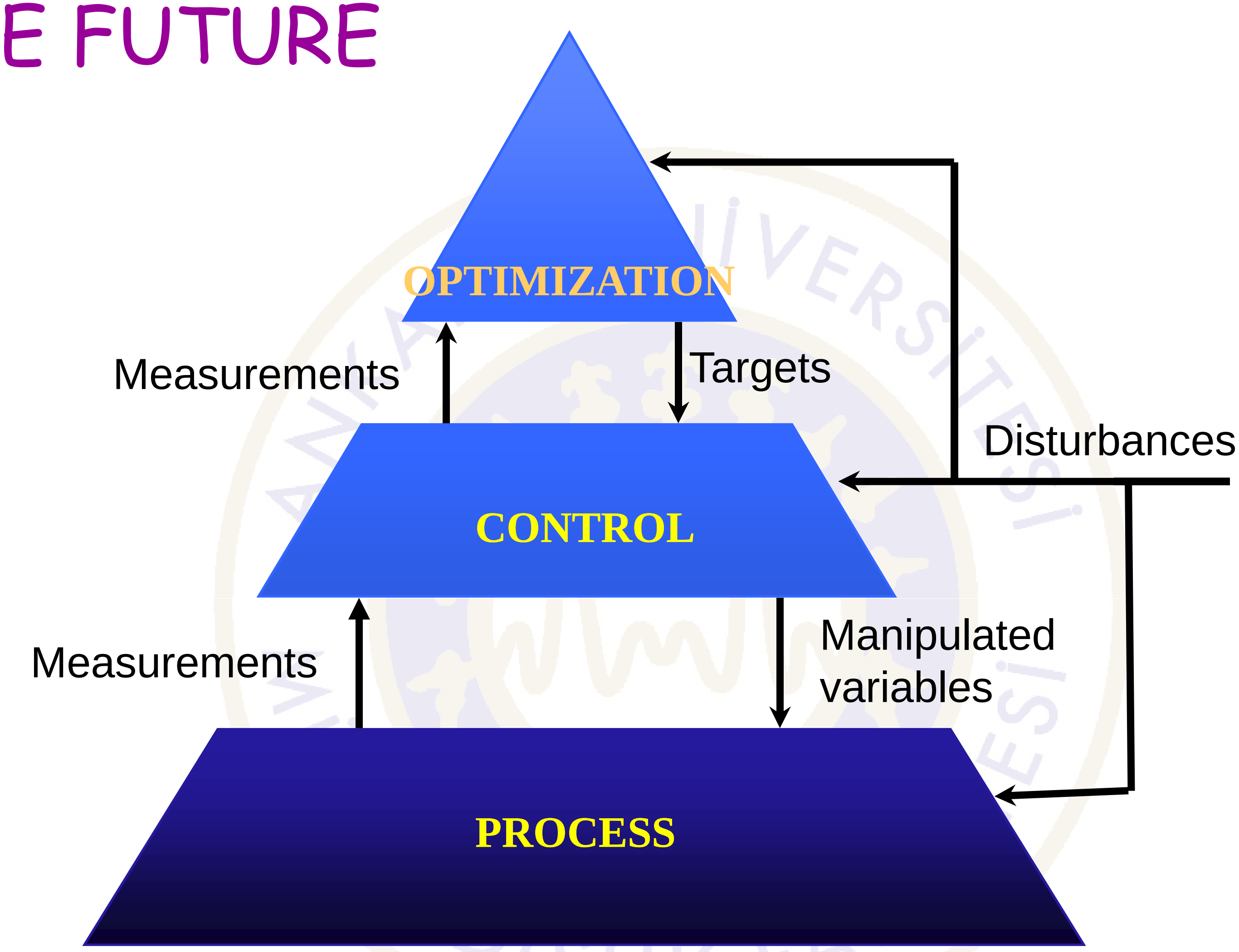
CONCLUSION

- Tools available
- Team work needed

  (Model calibration, validation)

  Close collaboration of industry/academia
- Savings possible with advanced optimization
- Integrated engineering approach necessary

THE FUTURE



OPTIMIZATION

Measurements

Targets

Disturbances

CONTROL

Measurements

Manipulated variables

PROCESS

INTEGRATED PROCESS SYSTEMS ENGINEERING

Work and contributions by

- Şaziye Balku
- Mehmet Yüceer
- Evrim Akyürek
- İlknur Atasoy

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&

THANKS FOR YOUR ATTENTION..