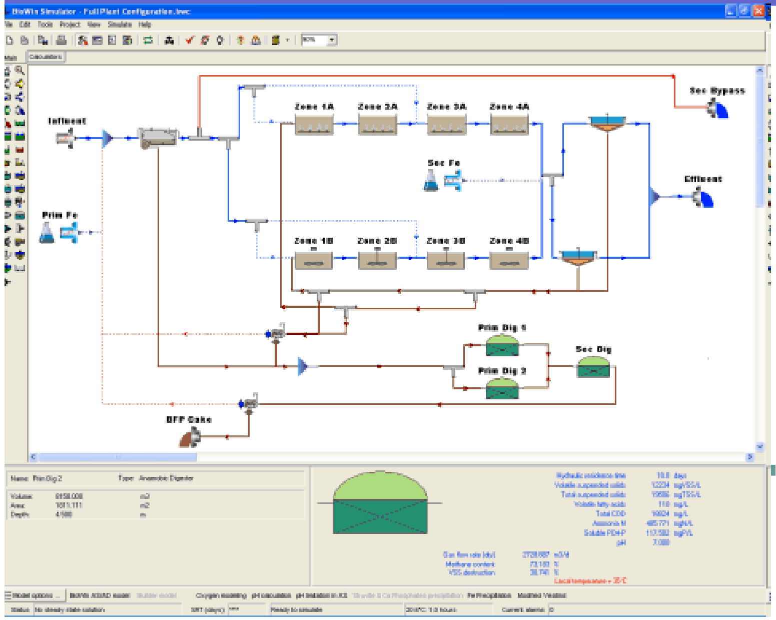
Chapter 5-Model-Based Design of WWTPs and Operation Variables



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Design and operation of activated sludge systems for carbon and nitrogen removal

- **Approach used: ASM1 mechanistic model**

- Based on mass balances: transfer and transformation terms
- Aims to obtain: reactor volumes, recycles, SRT, oxygen requirements, sludge production…
- Takes into account WW variation: seasonal scenarios (temp., loads, etc.)

- **Key factors for simulation:**

- Initial data: wastewater characteristics and bacterial coefficients
- Model selection: ASM1, ASM2, ASM2d, ASM3
- Simulation criteria and methods

Design and operation of activated sludge systems for carbon and nitrogen removal

- Raw wastewater characteristics in dry and wet weather conditions:

Traditionally: Q_{DW}, Q_{WW}, COD-BOD, TSS, NH_4-N, PO_4-P

Useful: filtered COD, org N, org P, variability

- Requirements in the effluent:

Total N < 10 or 15 mg N/L

Effluent COD, TSS

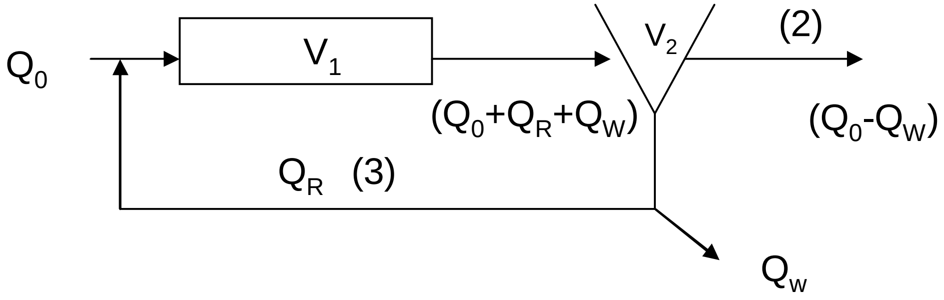
Useful for simulation: NH_4^+-N, NO_3^--N and PO_4^{3-}-P

- Summer and Winter Temperatures (key factor in biological-based systems)
- Minimum SRT or predefined for stable sludge (SRT is related to cell wash-out
- Aeration tank configuration (reactors, carrousel, SBR)

Others desirable:

- Sludge line returns
-Industrial inputs
- Maximum K_La

Mass Balances



$$V_1 \frac{dS_{S1}}{dt} = Q_0 S_{S0} + Q_R S_{S3} - (Q_0 + Q_R + Q_w) S_{S1} + V_1 r_{S_{S1}}$$

$$V_1 \frac{dX_{S1}}{dt} = Q_0 X_{S0} + Q_R X_{S3} - (Q_0 + Q_R + Q_W) X_{S1} + V_1 R_{X_{S1}}$$

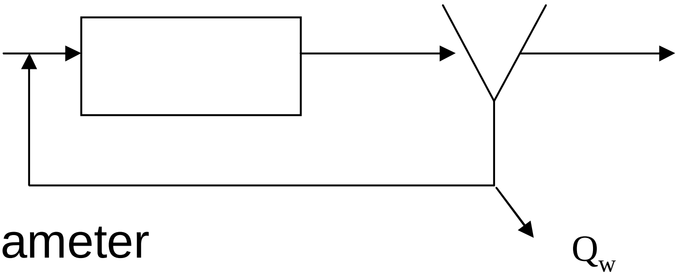
$$V_1 \frac{dX_{BH1}}{dt} = Q_0 X_{BH0} + Q_R X_{BH3} - (Q_0 + Q_R + Q_W) X_{BH1} + V_1 R_{X_{BH1}}$$

Design of WWTPs

- Simulation software do NOT provide the design automatically
- The optimization of the design is required through an iterative process in dynamic simulation
- The criteria used in the iterative process are based on the knowledge of cause-effect relationships (design-behavior parameters)
- Alternative: evaluation through simulation of designs made in spreadsheets

Carbon removal

$$S_{S,ef} = \frac{K_s\,(1+k_d SRT)}{SRT\,(\mu_H - k_d) - 1} \qquad SRT_{\min} = \frac{1}{\mu_{BH}}$$

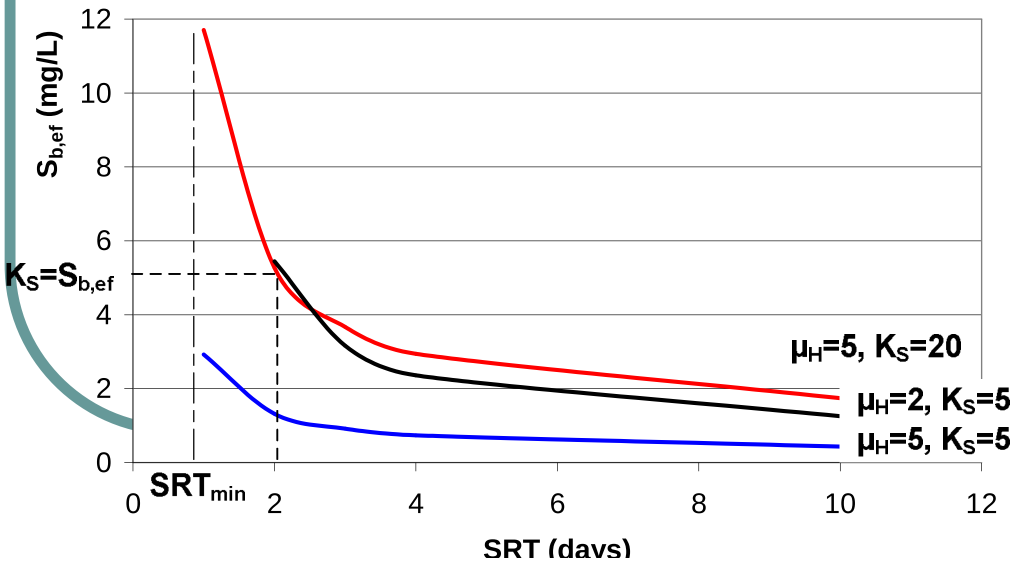


$S_{S,ef}$ does not depend on $S_{S,inf}$

SRT is the independent variable - design parameter

$$SRT = \frac{VX}{Q_W X_w}$$

Sensitive to μ_{H} (μ_{maxH}), K_s, k_d, Temp. Hydraulic Regulation



Design criteria 1: μ_H, K_s, k_d, determine the SRT needed to meet the $S_{S,ef}$ required

Carbon removal

Mass of Heterotrophic Bacteria → $M(X_{BH}) = V\,X_{BH} = \dfrac{Q_o(S_{so} - S_{sef})Y_H\,SRT}{1 + k_b\,SRT}$

At SRT>3-4 days → $Q_o(S_{SO} - S_{Sef}) \approx Q_o\,S_{SO}$

- No sensitive to μ_H, K_S

- SRT is the independent variable

- 1+ $k_b \cdot$SRT determines that MX_{HB} is no linearly proportional to SRT

Mass of Heterotrophic Bacteria debris → $M(X_o) = VX_o = f_P\,k_b\,M(X_{BH})\,SRT$

Mass of inert VSS → $\begin{cases} (X_I) = X_{IO}\,SRT/HRT \\ M(X_I) = V(X_I) = Q_o\,X_{IO}\,SRT \end{cases}$

Carbon removal

Idem for $M(X_{IN})$ → The Mass of inorganic Materials

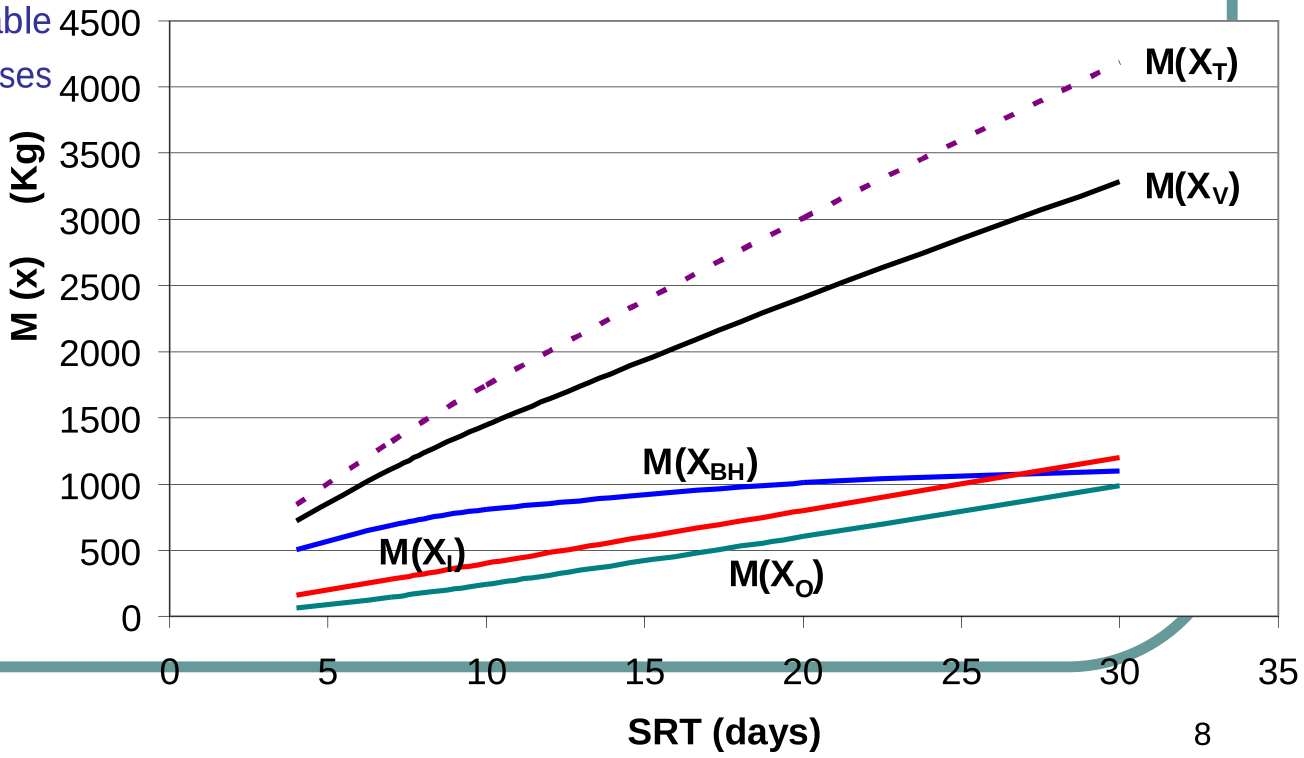
- Linear link to SRT
- SRT/HRT is the acumulation factor for particulates

$$M(X_T) = M(X_{BH}) + M(X_o) + M(X_I) + M(X_{IN})$$

$M(X_S) \approx 0$

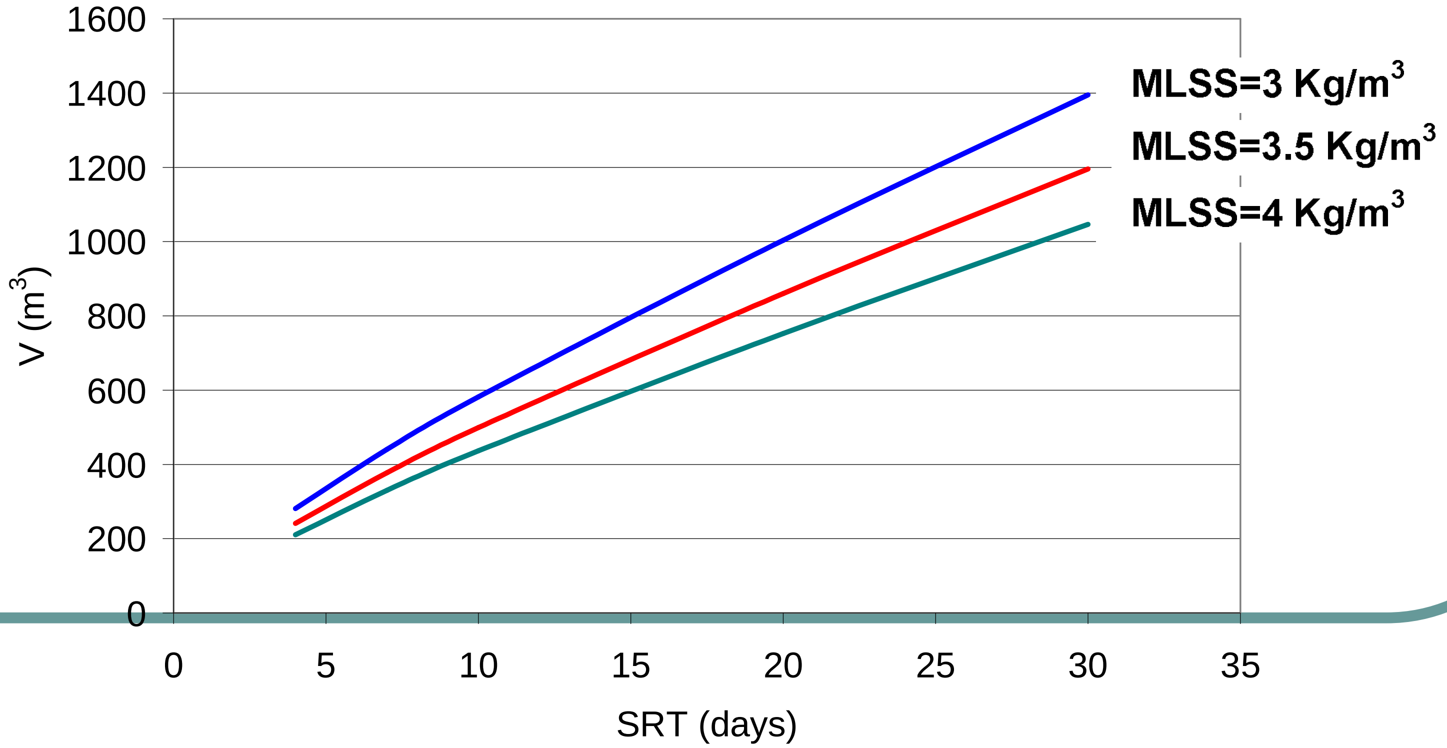
Design criteria 2: the selected SRT determines the $M(X_j)$, where $_j$ is $_{HB,\ O,\ I,\ IN}$ and $M(X_{T)} = V \cdot X_T$

- SRT is the independent variable
- Stability of the sludge increases with SRT



Carbon removal

- $M(X_T) = f$ (SRT)
- For preselected X_T: X_T Design → $M(X_T)$ is imposed by WW characteristics, microbial kinetics and SRT
- SRT determines V (2nd design criteria) and HRT
- $V = M(X_T) / X_T$ design



Carbon removal

Sludge Production (P_X) = $\frac{M(X_T)}{SRT}$

- Sensitive to: X_{I0}, X_{INO}, k_d, temp, f_P, Y
- P_X decreases with SRT due to decay

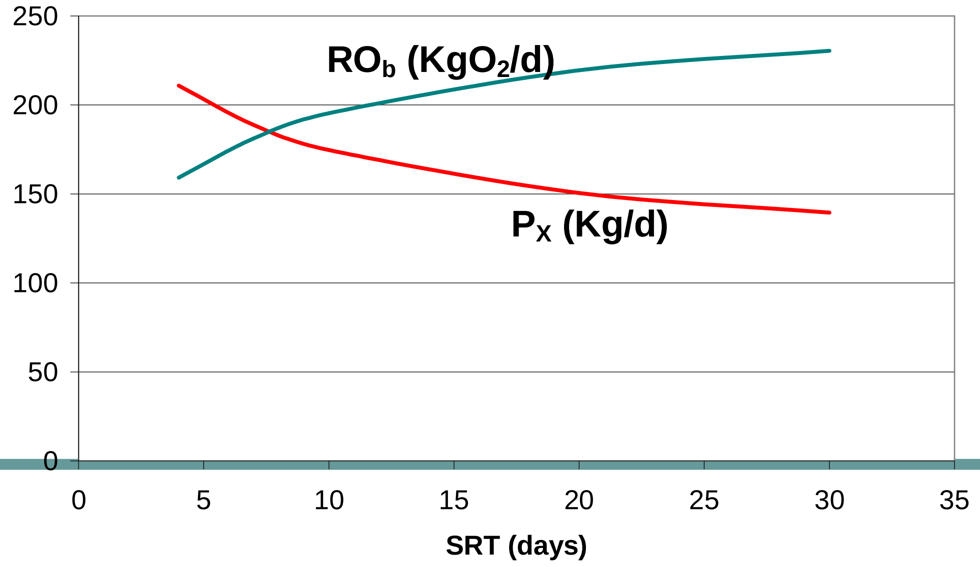
Oxygen Requirements (RO_b)

$RO_b = V \cdot OUR =$

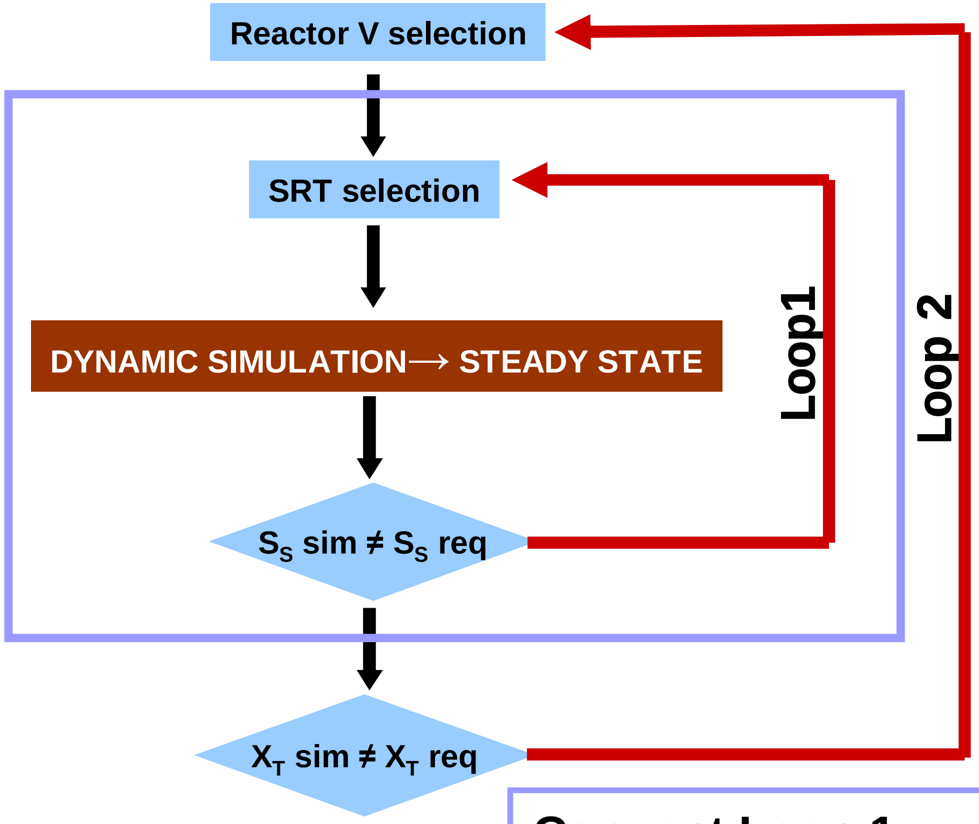
$(1-Y_H) \cdot Q_0 \cdot bCOD + (1-f_p) \cdot k_d \cdot M(X_{BH})$

RO_b increases with SRT due to decay

Overall mass balance for carbon (C) is fulfilled



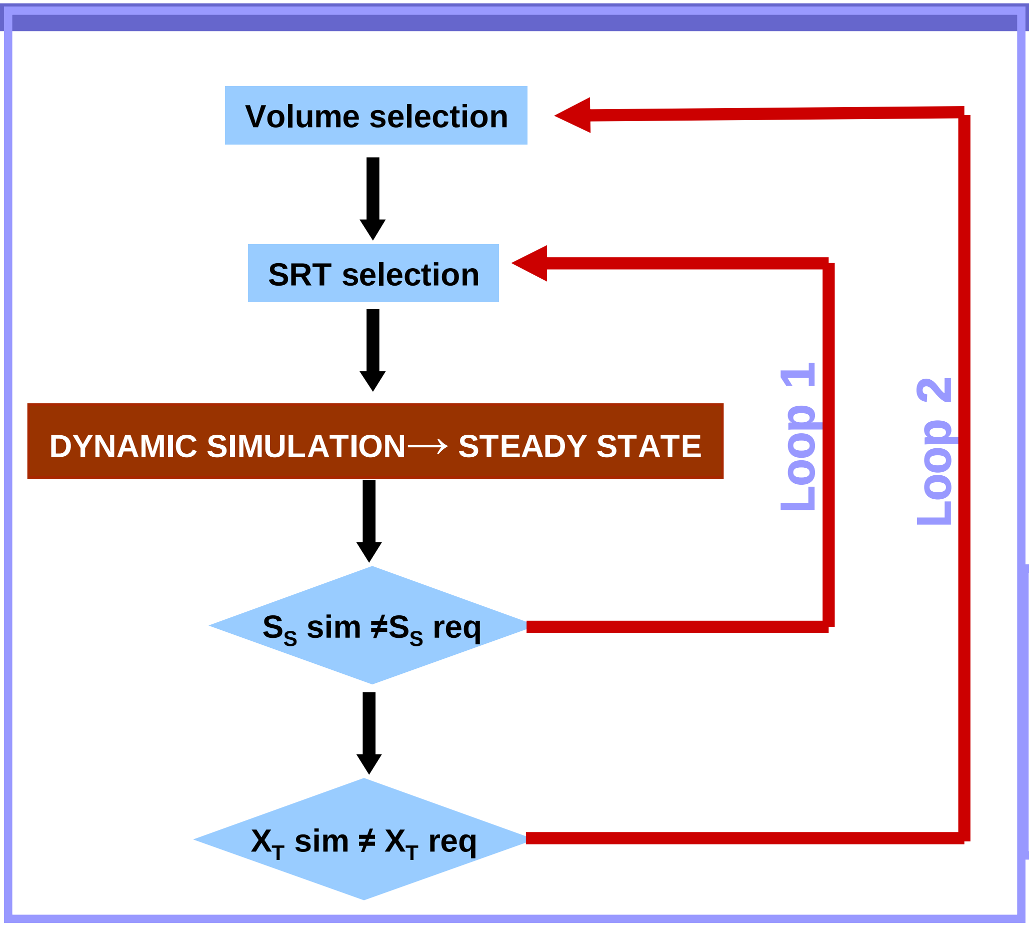
Carbon Removal



Concept Loop 1:

$S_{S,ef}$ only depends on SRT

Carbon removal



Volume selection

SRT selection

DYNAMIC SIMULATION→ STEADY STATE

S_S sim ≠ S_S req

X_T sim ≠ X_T req

Loop 1

Loop 2

Concept Loop 1:

$S_{S,ef}$ only depends on SRT

Concept Loop 2:

SRT determines

$M(X_T)=V \cdot X_T= P(X_T)$ SRT

Nitrification

$$S_{NH,ef} = \frac{K_{NH}(1+k_{bn}SRT)}{SRT(\mu_A - k_{bn}) - 1}$$

$$SRT_{\min} = \frac{1}{\mu_A - k_{bn}} \approx 2\ days\,(13^o C)$$

To meet $S_{NH,ef}$ = 1 mgN/L

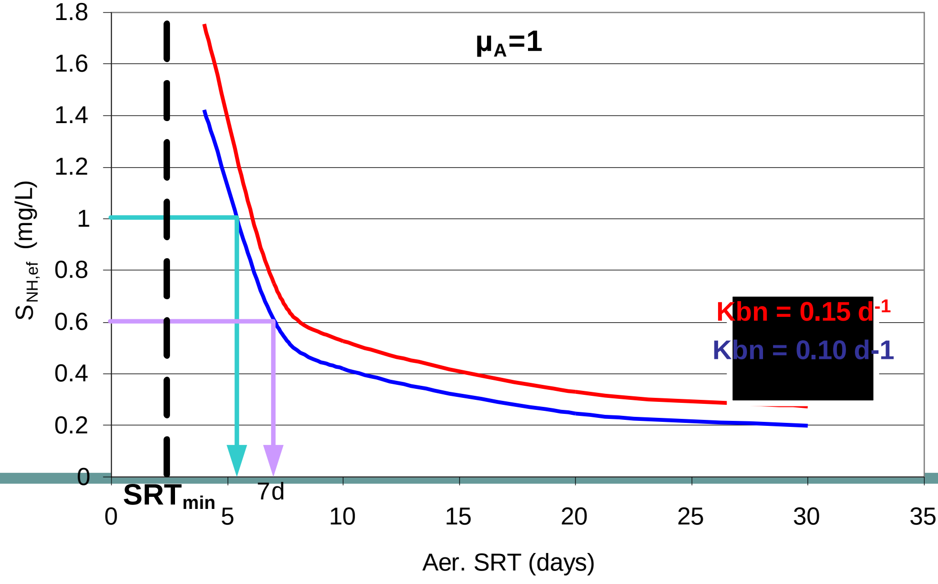
For constant Inf. Aerobic SRT ≈ 5 days.

For variable Inf. Aerobic SRT ≈ 5 *1,4 (safety factor) ≈ 7 days.

Sensitive to μ_A (μ_{maxA}), K_{NH}, k_{bn}, Temp

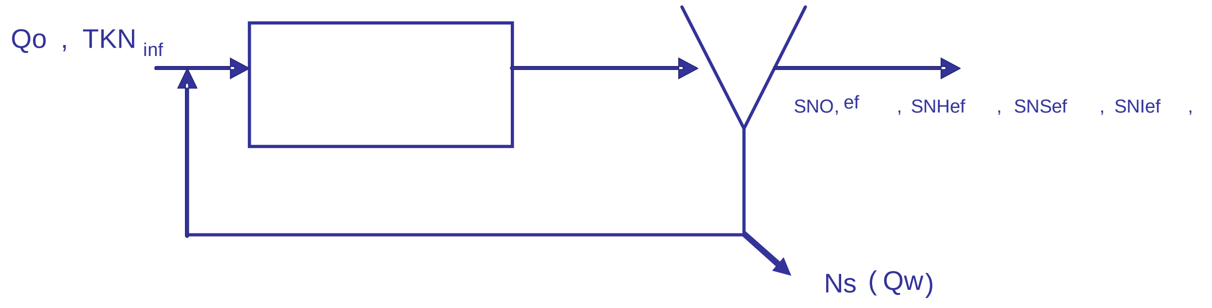
Plug flow in the aeration tank better than completely mixed → Reactor in series

High K_La at the head of the aeration tank



Nitrification capacity

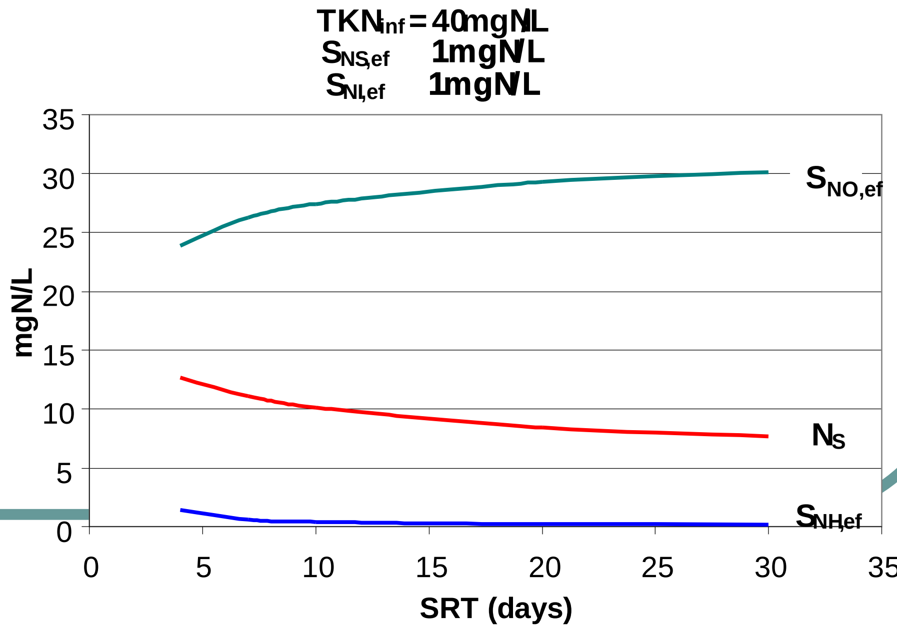
Overall N mass balance



$$NC = S_{NO,ef} = Q_o/(Q_o - Q_w)TKN_{inf} - S_{NH,ef} - S_{NS,ef} - S_{NI,ef} - Q_w N_S/(Q_o - Q_w)$$

$$N_S = fn \frac{M\,(X_V)}{SRT \cdot Q_w}$$

$f_n \approx 0.07$ mg N/mg DQO(X_V)



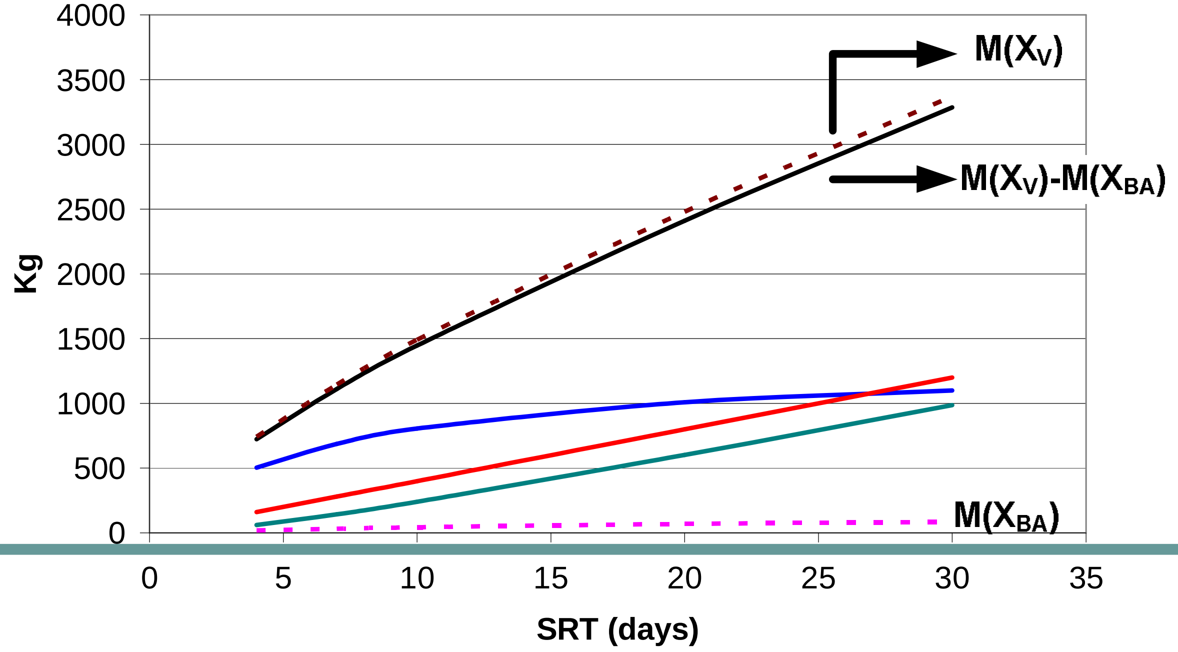
Carbon Removal +Nitrification

$$M(X_{BA}) = V \cdot X_{BA} = \frac{Q_O\, CN\, Y_A\, SRT}{1 + k_{bn}\, SRT}$$

$$M(X_V) = f(Q_O, bCOD_{\inf}, Y_H) \qquad M(X_{BA}) <<< M(X_V)$$

$$\left.\begin{array}{l} COD_{\inf} >> CN \\ Y_H >> Y_A \end{array}\right\} \Rightarrow \quad P_X(\Delta C + Nit) \approx P_X(\Delta C)$$

Very low contribution of nitrification to sludge production

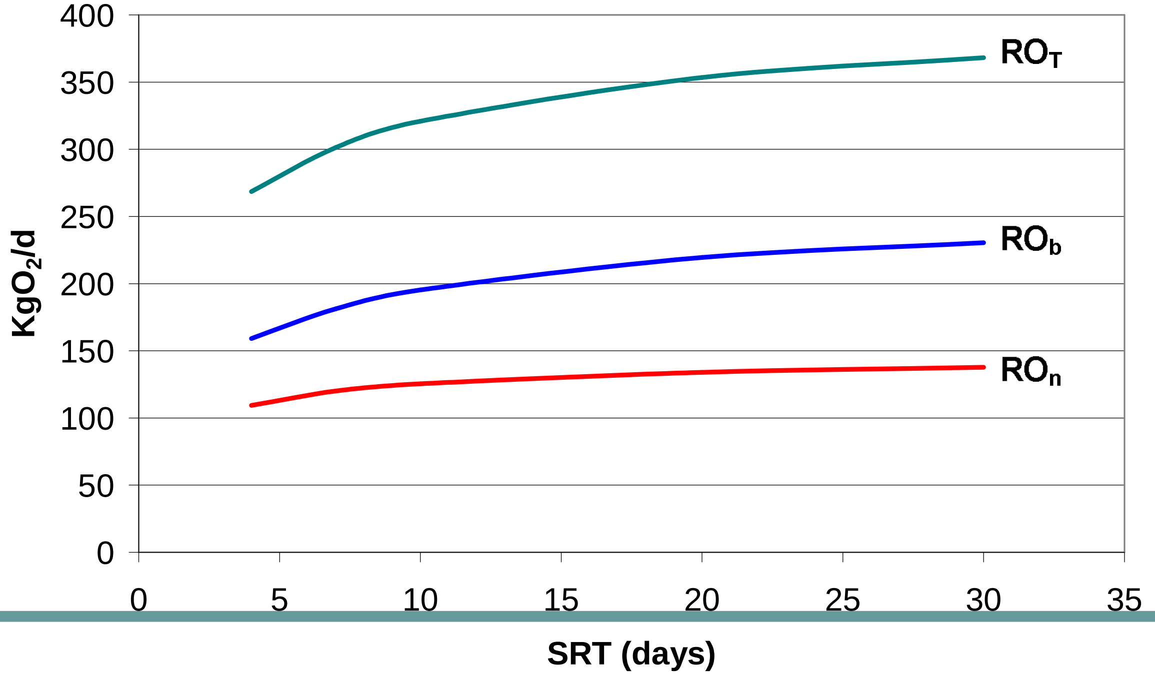


Carbon Removal + Nitrification

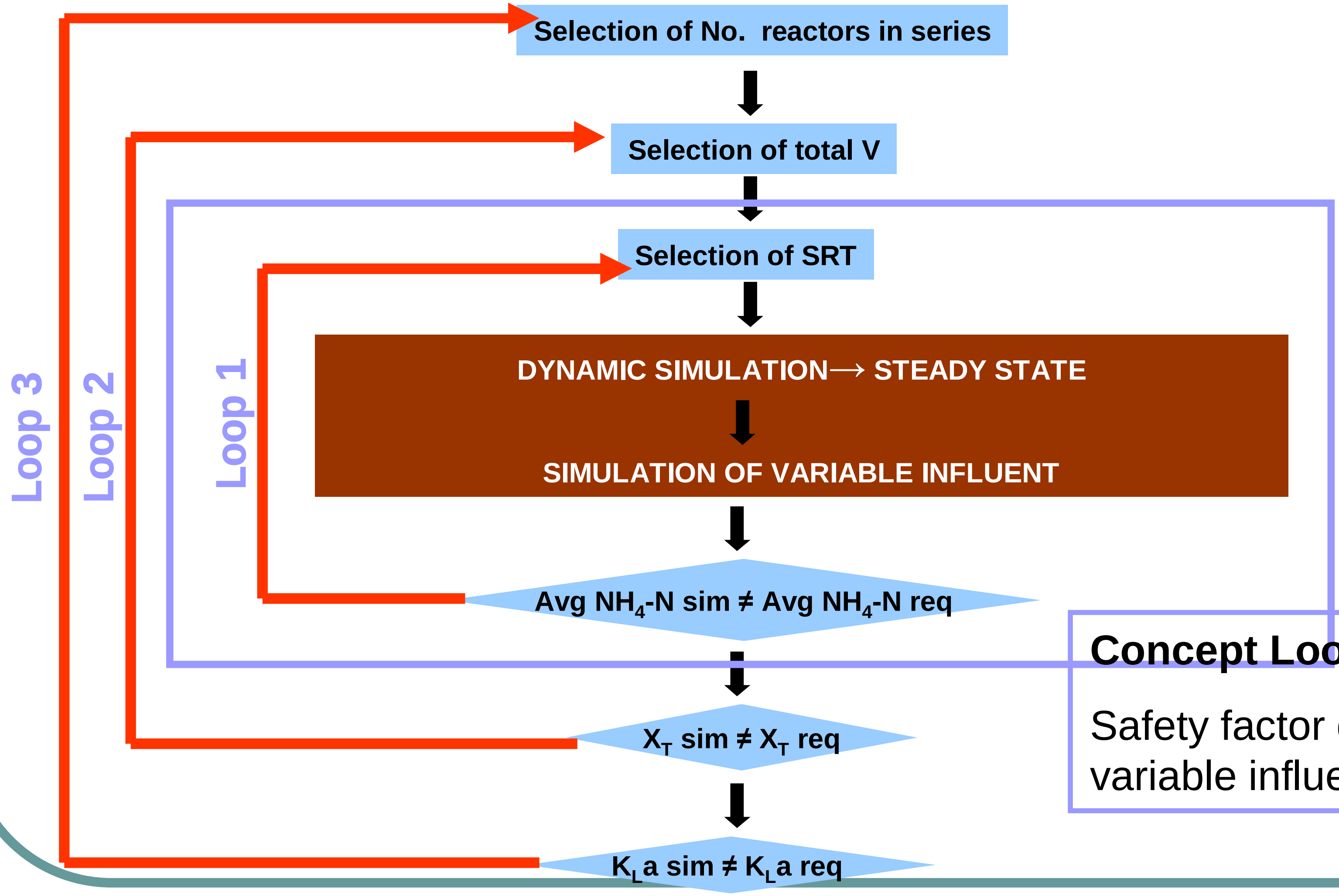
$RO_n = 4.57 \cdot Q_O \cdot CN$

$RO_T = RO_b + RO_n$

High contribution of nitrification to oxygen requirements



Nitrification



Selection of No. reactors in series

Selection of total V

Selection of SRT

DYNAMIC SIMULATION ⟶ STEADY STATE

SIMULATION OF VARIABLE INFLUENT

Avg NH_4-N sim ≠ Avg NH_4-N req

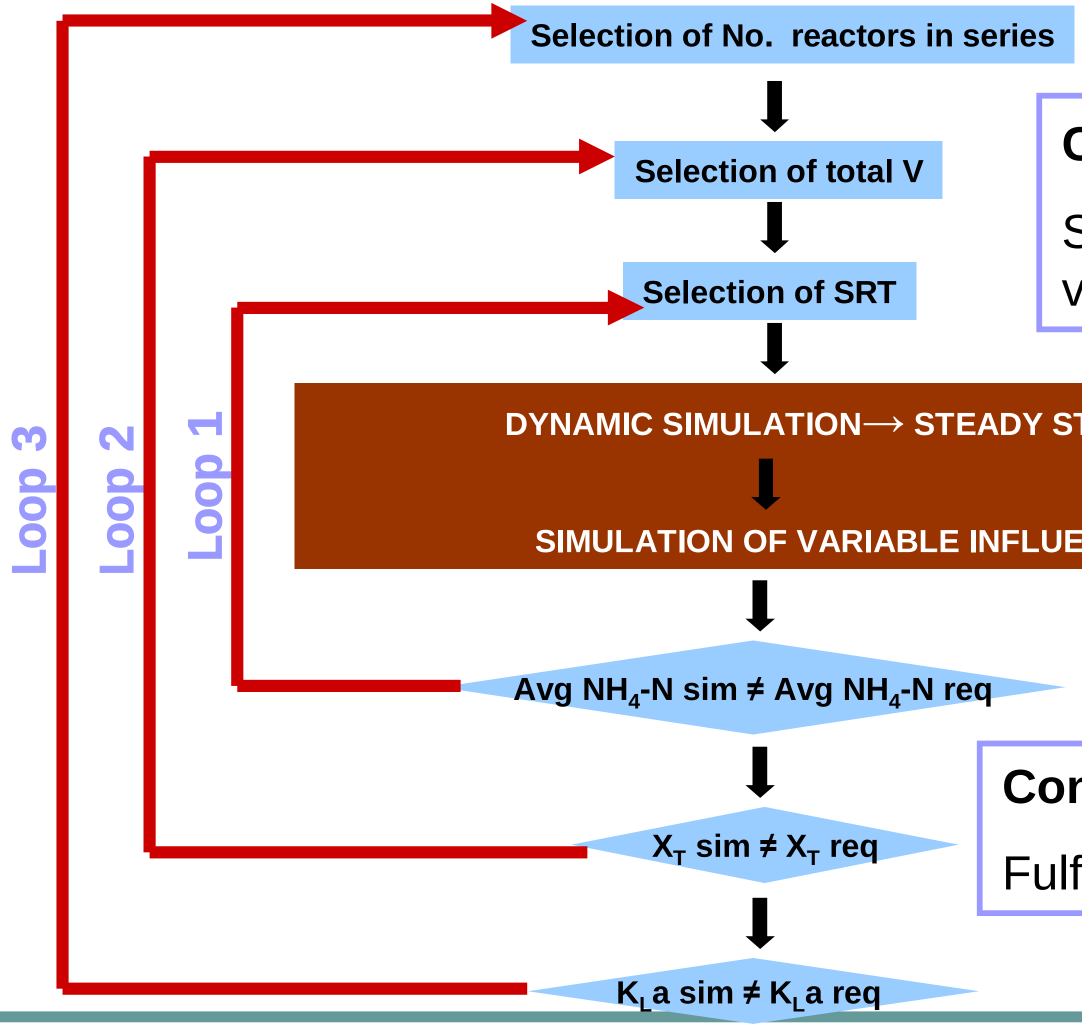
X_T sim ≠ X_T req

K_La sim ≠ K_La req

Concept Loop 1:

Safety factor due to variable influent

Nitrification



Selection of No. reactors in series

Selection of total V

Selection of SRT

DYNAMIC SIMULATION ⟶ STEADY STATE

SIMULATION OF VARIABLE INFLUENT

Avg NH_4-N sim ≠ Avg NH_4-N req

X_T sim ≠ X_T req

K_La sim ≠ K_La req

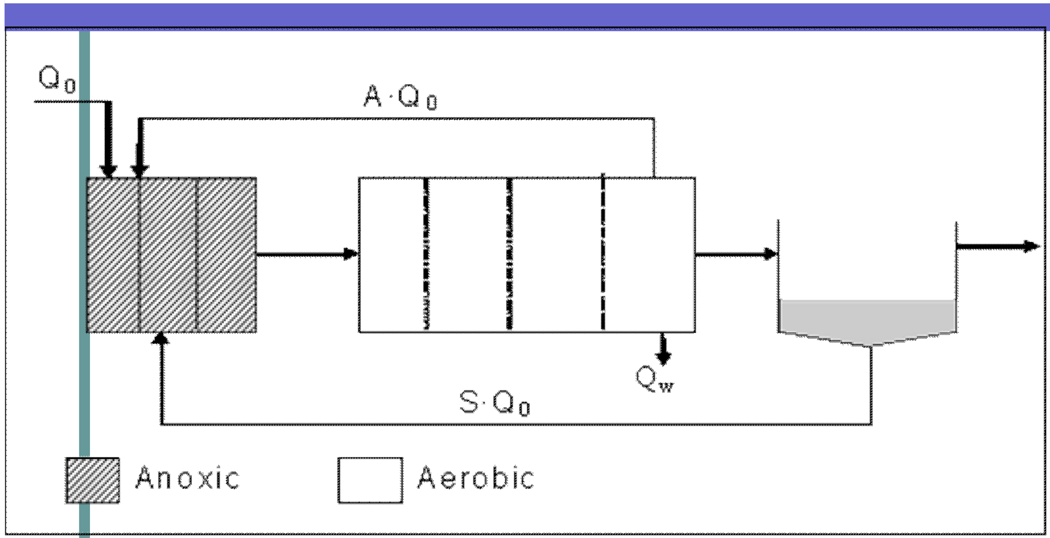
Concept Loop 1:

Safety coefficient due to variable influent

Concept Loop 3:

Fulfillment of max. K_La

Predenitrification-Nitrification



- Design Parameters
  - F_X: Anoxic fraction
  - $SRT_{gl} = SRT_{ae} + SRT_{anx} = SRT_{ae} + SRT_{gl} \cdot F_X$
  - $SRT_{ae} \approx$ 7 days (13º C)
  - A_O: Optimun internal recycle fraction (A)
  - S: External recycle fraction (≈1)

- Effluent Requirements
  - N_T: 10; 15 mg N/L.
  - $S_{NH,ef} \approx$ 1-2 mg N/L.
  - $S_{NO,ef} \approx$ 5-6; 10-11 mgN/L.

- From overall N balance: $S_{NO,ef}$= CN-DP
  - DP= DP1+DP2
  - DP1: Removal of NOx due to S_S
  - DP2: Removal of NOx due to X_S

Predenitrification-Nitrification

- For $A \leq A_O$ → Not all the denitrification potential of the influent WW is used $S_{NO,ax} = 0$

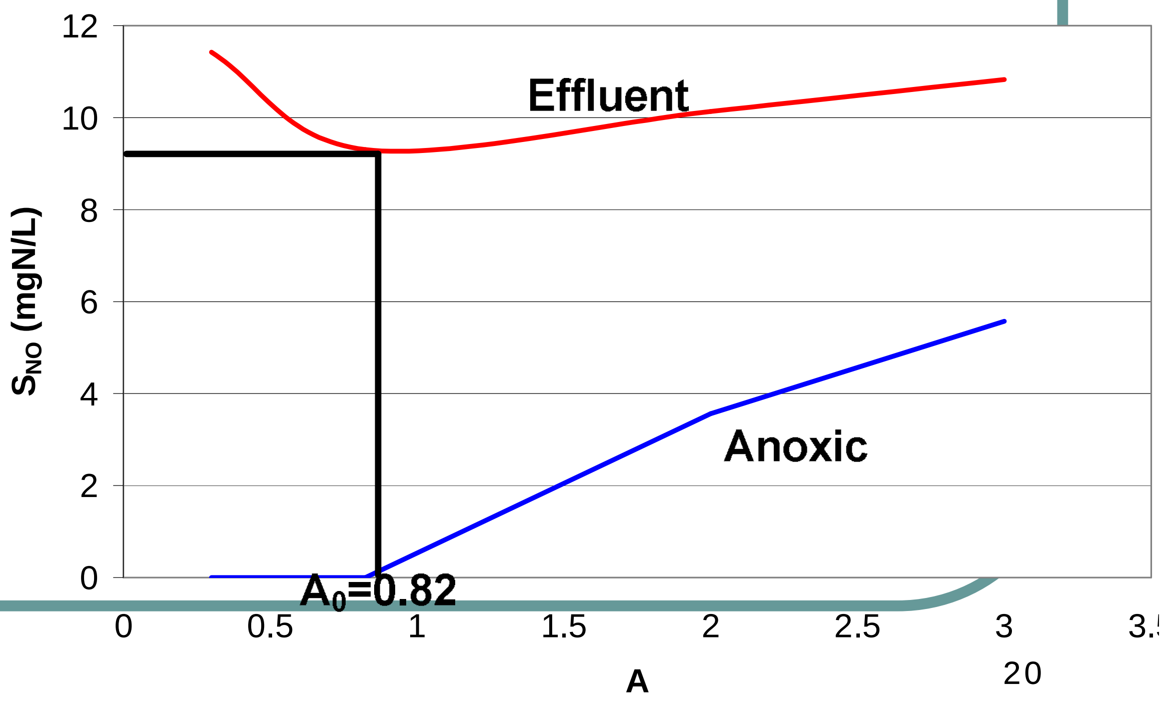
- For $A > A_O$

$S_{NO,ef} = CN\text{-}DP$

$S_{NO,ax} > 0$

Harmful effects of A → Removal of SS_{inf}

$$SS_{inf,av} = SS_{inf} - A \cdot 2mgO_2/L \cdot 3mgSS_{inf}/mgO_2$$

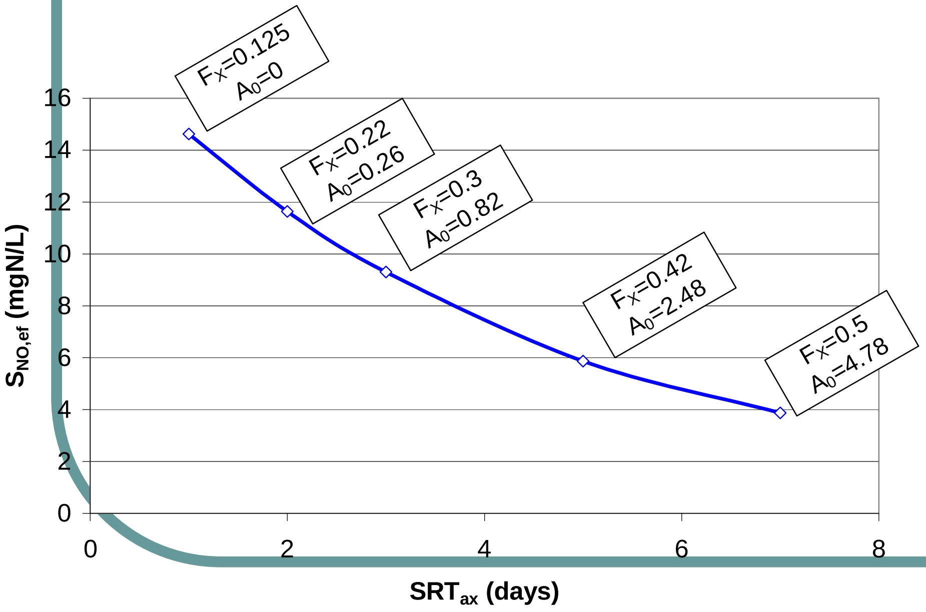

Effect of A for F_X=0,3

Predenitrification-Nitrification

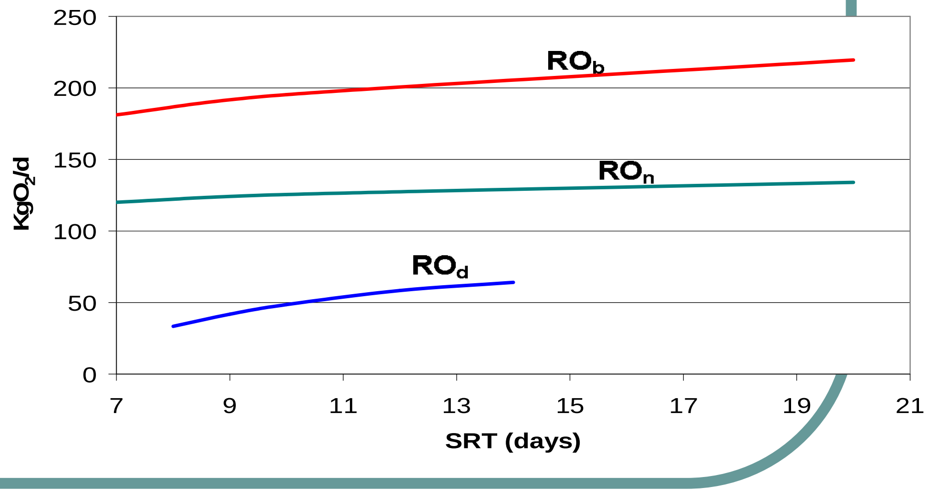
- $S_{NO,ef}$ = CN – DP
- CN = f (TKN_{inf})
- Maximum DP = f ($S_{Sinf,av}$, X_{Sinf}, SRT_{anx})
- $S_{NO,ef}$ = f [$(COD/TKN)_{inf}$, SRT_{ax}]

Effect of SRT_{ax}, SRT_T, F_X

- $RO_d = 2.86 \cdot Q_0 \cdot DP$
- $RO_T = RO_b + RO_n - RO_d$

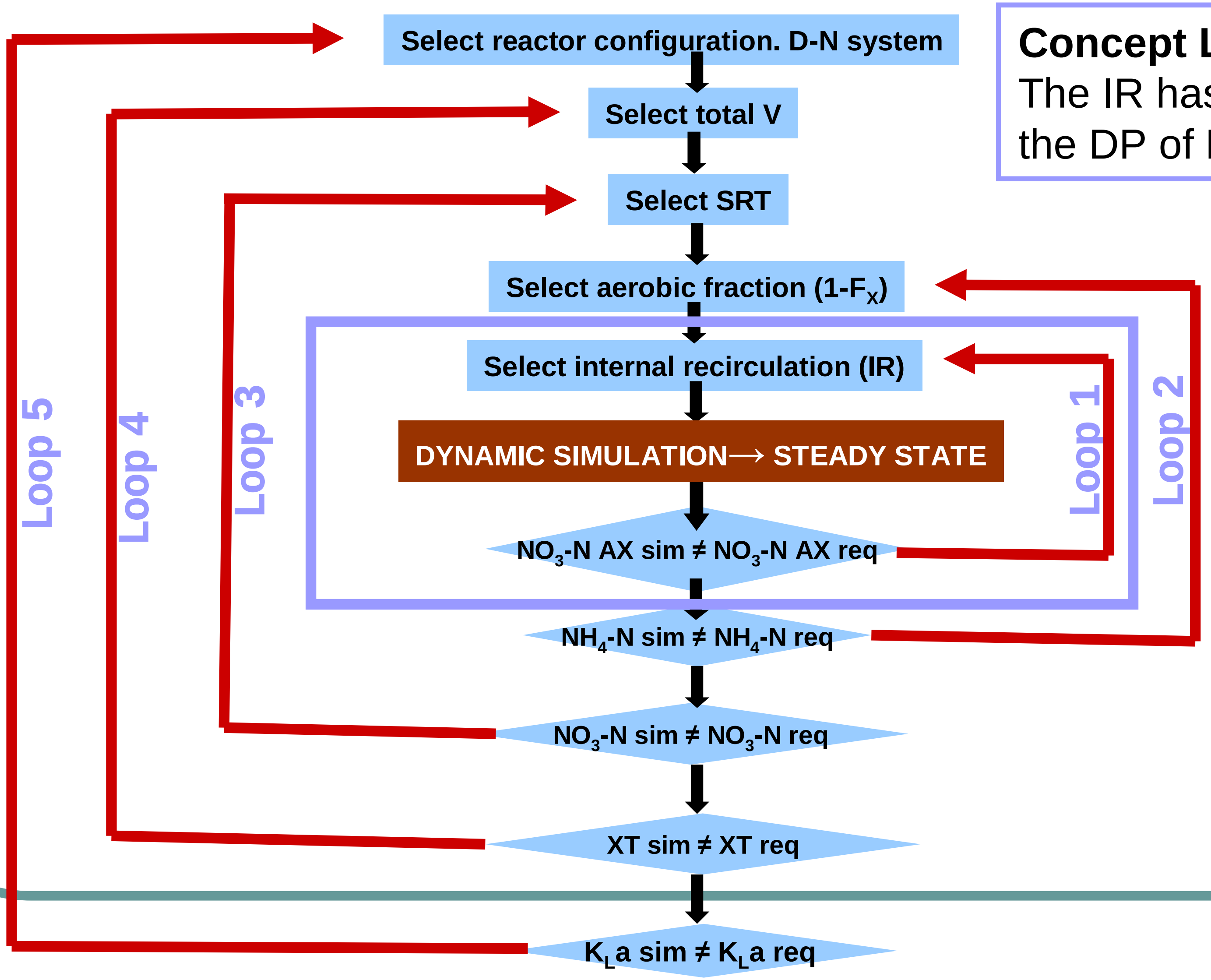


$SRT_T = SRT_{ae} + SRT_{ax}$
SRT_{ae} = 7 days



Nitrogen Removal

Concept Loop 1:
The IR has to deplete the DP of F_X



Select reactor configuration. D-N system

Select total V

Select SRT

Select aerobic fraction ($1-F_X$)

Select internal recirculation (IR)

DYNAMIC SIMULATION⟶ STEADY STATE

NO_3-N AX sim ≠ NO_3-N AX req

NH_4-N sim ≠ NH_4-N req

NO_3-N sim ≠ NO_3-N req

XT sim ≠ XT req

K_La sim ≠ K_La req

Loop 1

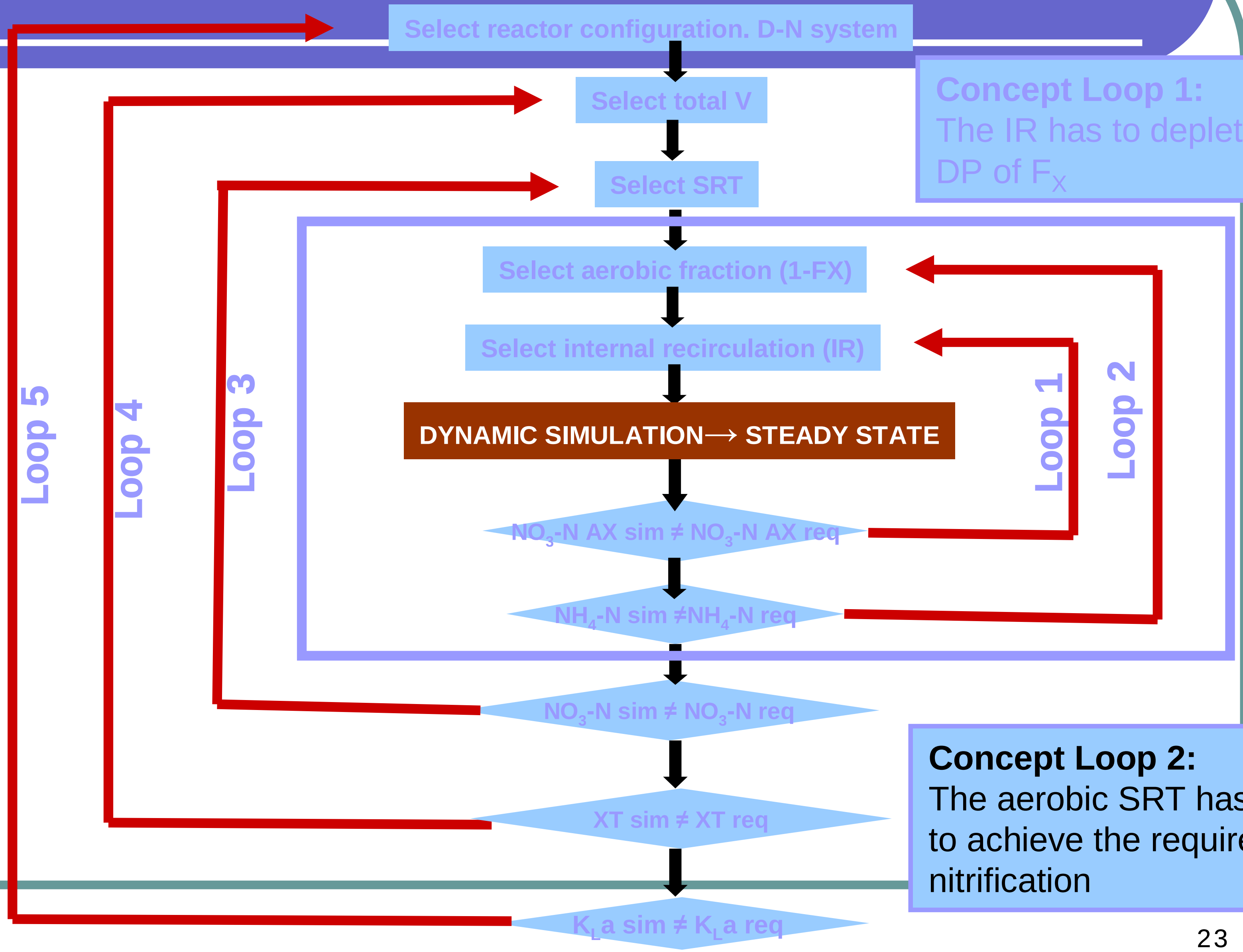
Loop 2

Loop 3

Loop 4

Loop 5

Nitrogen removal



Select reactor configuration. D-N system

Select total V

Select SRT

Select aerobic fraction (1-FX)

Select internal recirculation (IR)

DYNAMIC SIMULATION⟶ STEADY STATE

NO_3-N AX sim ≠ NO_3-N AX req

NH_4-N sim ≠NH_4-N req

NO_3-N sim ≠ NO_3-N req

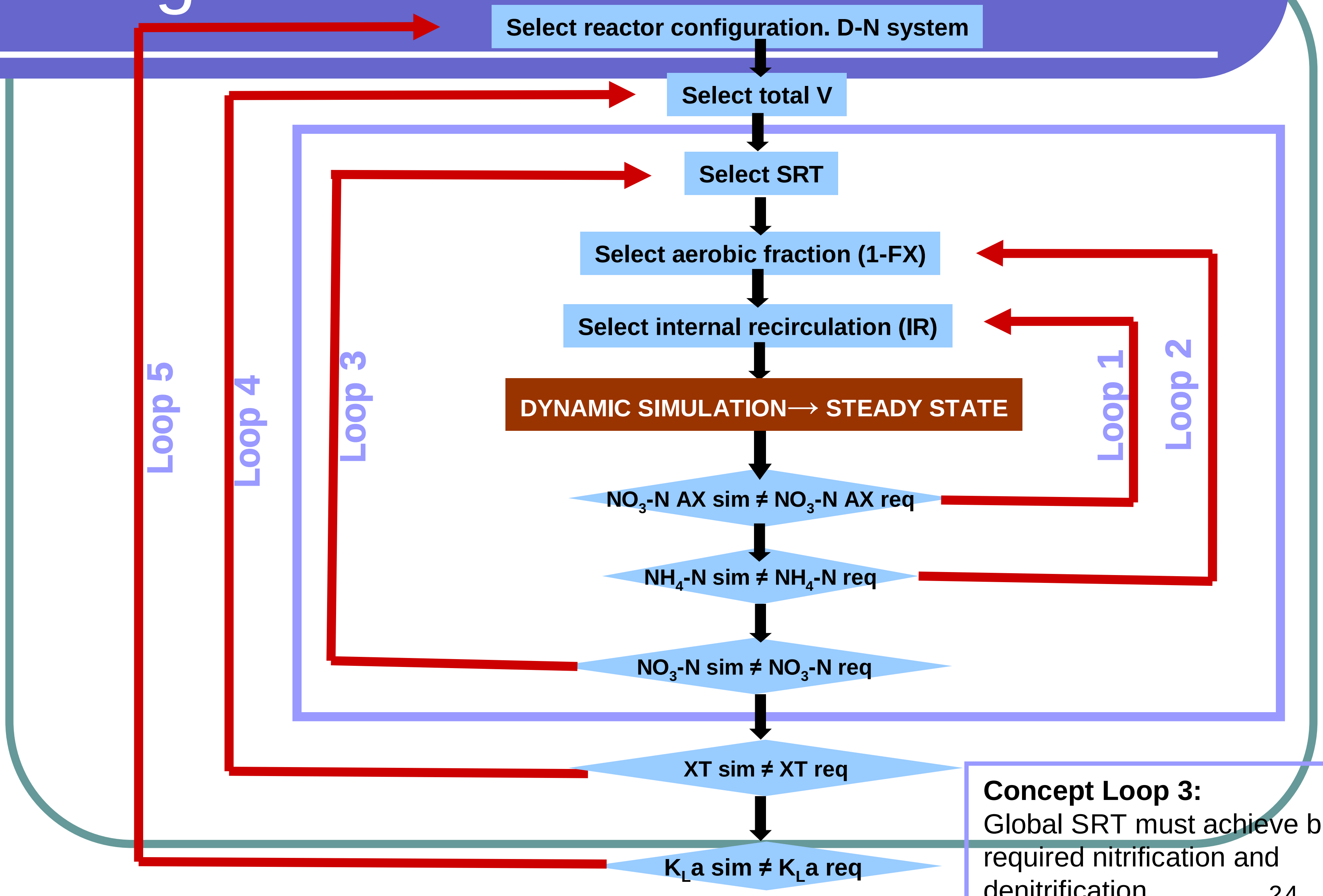
XT sim ≠ XT req

K_La sim ≠ K_La req

Concept Loop 1:
The IR has to deplete DP of F_X

Concept Loop 2:
The aerobic SRT has to achieve the required nitrification

Nitrogen removal



Select reactor configuration. D-N system

Select total V

Select SRT

Select aerobic fraction (1-FX)

Select internal recirculation (IR)

DYNAMIC SIMULATION⟶ STEADY STATE

NO_3-N AX sim ≠ NO_3-N AX req

NH_4-N sim ≠ NH_4-N req

NO_3-N sim ≠ NO_3-N req

XT sim ≠ XT req

K_La sim ≠ K_La req

Loop 5

Loop 4

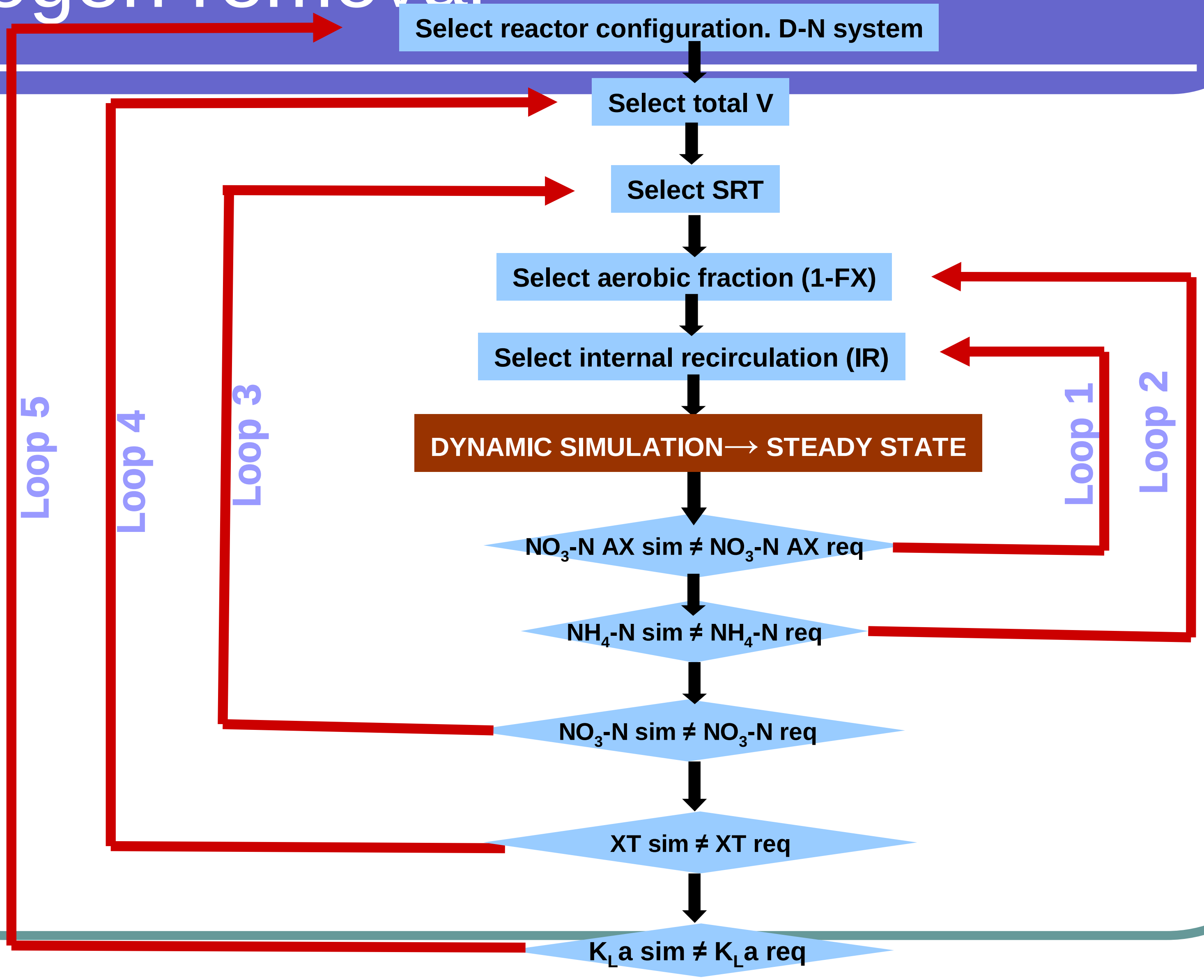
Loop 3

Loop 1

Loop 2

Concept Loop 3:
Global SRT must achieve both required nitrification and denitrification

Nitrogen removal



Select reactor configuration. D-N system

Select total V

Select SRT

Select aerobic fraction (1-FX)

Select internal recirculation (IR)

DYNAMIC SIMULATION ⟶ STEADY STATE

NO_3-N AX sim ≠ NO_3-N AX req

NH_4-N sim ≠ NH_4-N req

NO_3-N sim ≠ NO_3-N req

XT sim ≠ XT req

K_La sim ≠ K_La req

Loop 1

Loop 2

Loop 3

Loop 4

Loop 5

MX_j, P_X, RO: results from simulation

Conclusions

- Design through simulation provides with a high added value
  - Makes process optimization easier
  - More detailed information about the reactors
  - Configuration flexibility and system interaction
  - Makes knowledge acquisition easier
- Key: to have a high and clear knowledge on…
  - Initial data
  - Mathematical model to be applied
  - Design parameters – behavior relationships
  - The criteria for the iterative simulation process

Operation Variables

Introduction: Objectives and Variables

Objectives of WWTP Operation and Control

1- To maintain the plant operative

- Maintain an active biomass within the biological reactors
- Maintain operative the basic unit processes (pretreatment, activated sludge tanks, settlers, digesters, etc.)

2- To fulfil the effluent quality requirements

- COD, N (NH_4, NO_3), P

3- To respond successfully to possible perturbations

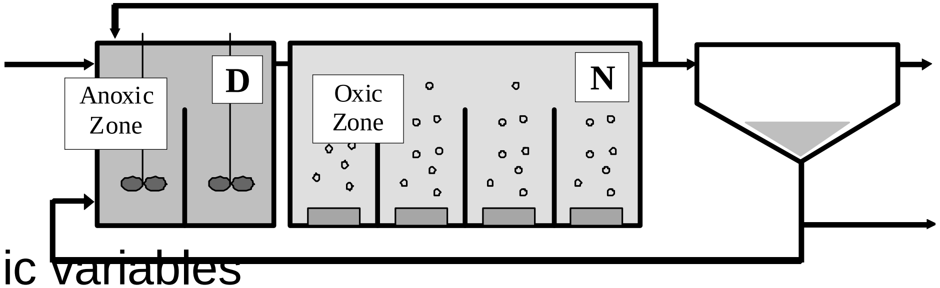
- Overloads (hydraulic or concentration), toxicity, seasonal variations in load and temperature

4- To reduce operation costs

- Aeration
- Sludge treatment

Introduction: Objectives and Variables

Operational Variables in a WWTP (DN)



1- Hydraulic variables

- Influent Flow: Equalisation tanks, Step-feed
- Wastage flow
- Recirculation of Settled Sludge
- Internal Recirculation of Nitrates

2- External supply of substances

- Physical/chemical P removal
- Addition of extra C for denitrification

3- Aeration

- Supply of air or oxygen
- Facultative zones in the reactors

Introduction: Objectives and Variables

Limits for Plant Operation

Variable	Lower limit	Upper limit
Influent Flow	Hydraulic capacity of the sewers and the equalisation tanks	Hydraulic capacity of the clarifier
Wastage Rate	SRT required (Nitrification)	SRT required (Solids flux to the settler)
Sludge Recirculation	Sludge blanket level Retention time in the settler	Hydraulic load Dilution of the sludge
Nitrates Recirculation	Nitrates demand	Denitrification capacity
Chemicals Addition	P requirements in the effluent	Economical cost
Carbon Addition	Denitrification capacity	Economical cost Excess of C load
Air flow	Respiration rate	Economical cost Excess of stirring

Operational variables

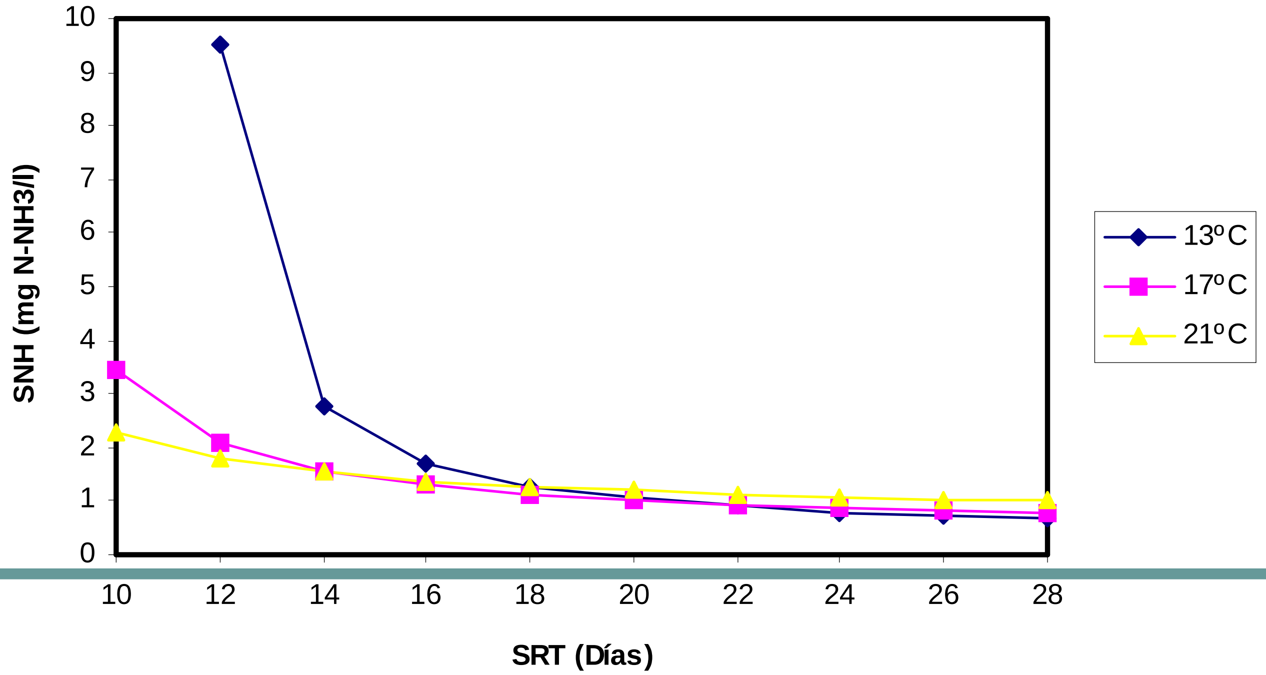
- Wastage Rate: Solids Retention Time
  - SRT: average time the solids stay in the process
    - Steady-state concept (sludge age)
    - SRT = (mass of solids) / (output flux of solids)
    - SRT ≈ Reactors Volume / Wastage rate
  - Crucial process parameter: Significant influence in
    - The bacterial populations that are or not retained within the process (wash-out of those whose μmax < SRT
    - The MLSS in the reactors
    - The sludge production (relevant operation cost)
    - Endogenous respiration rate
    - TSS fractions (X_{BH}, X_O, etc…)

Operational variables

Wastage Rate: Solids Retention Time

Influence of SRT in nitrification

- Determines the minimum SRT for stable nitrification
- Significant influence of process temperature
- Important: response time for recovering nitrification

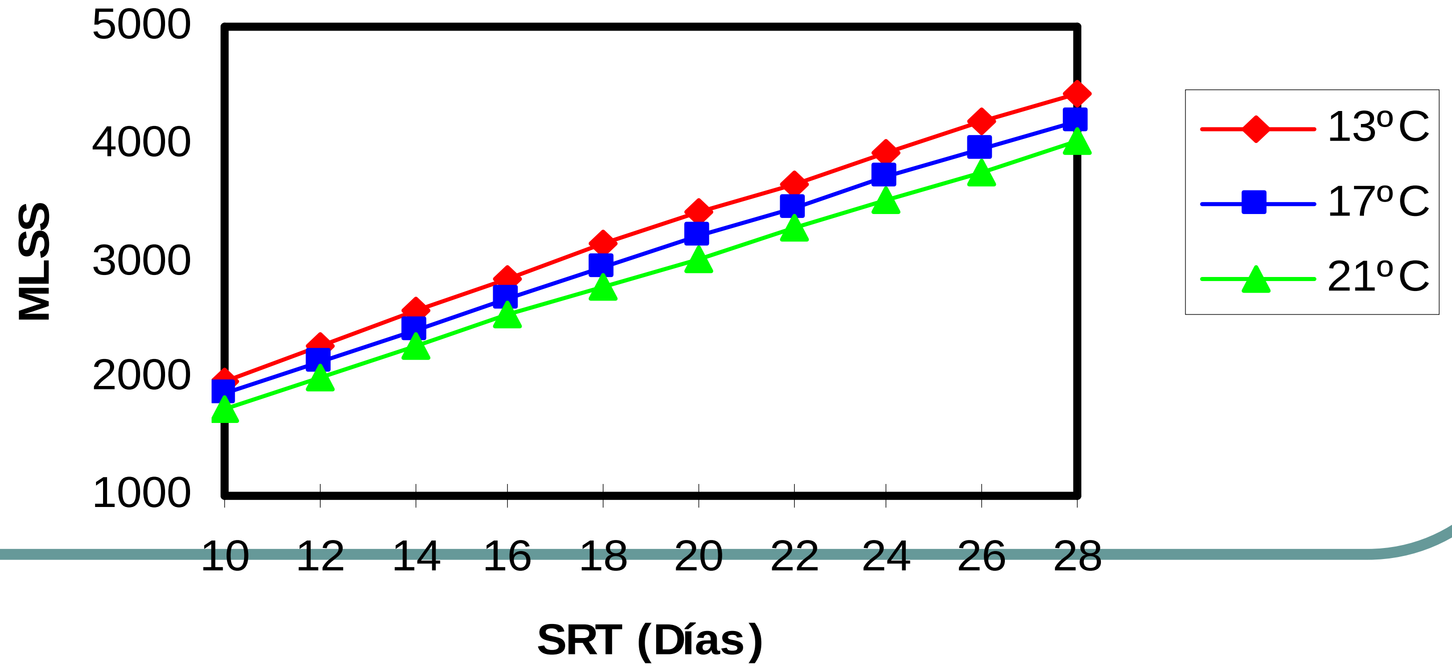


Operational variables

Wastage Rate: Solids Retention Time

Influence of SRT in MLSS

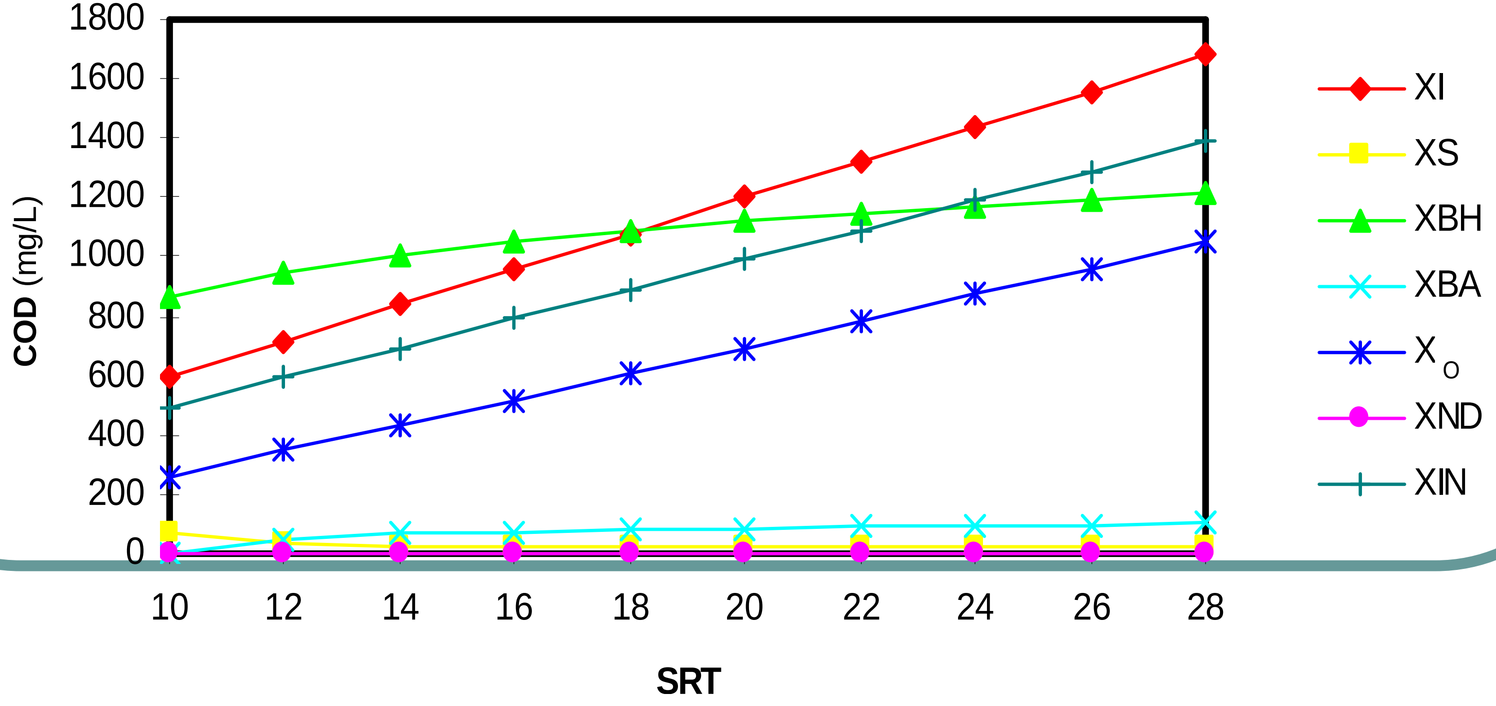
- The relationship is almost linear
- Additional influence of Tª: reduction of sludge production in summer



Operational variables

Wastage Rate: Solids Retention Time

- Influence of SRT in TSS fractions
  - Progressive stabilisation of the biomass at high SRT
  - Linear accumulation of inert solids (Use of Vr)
  - Reduction in the active fraction of the sludge

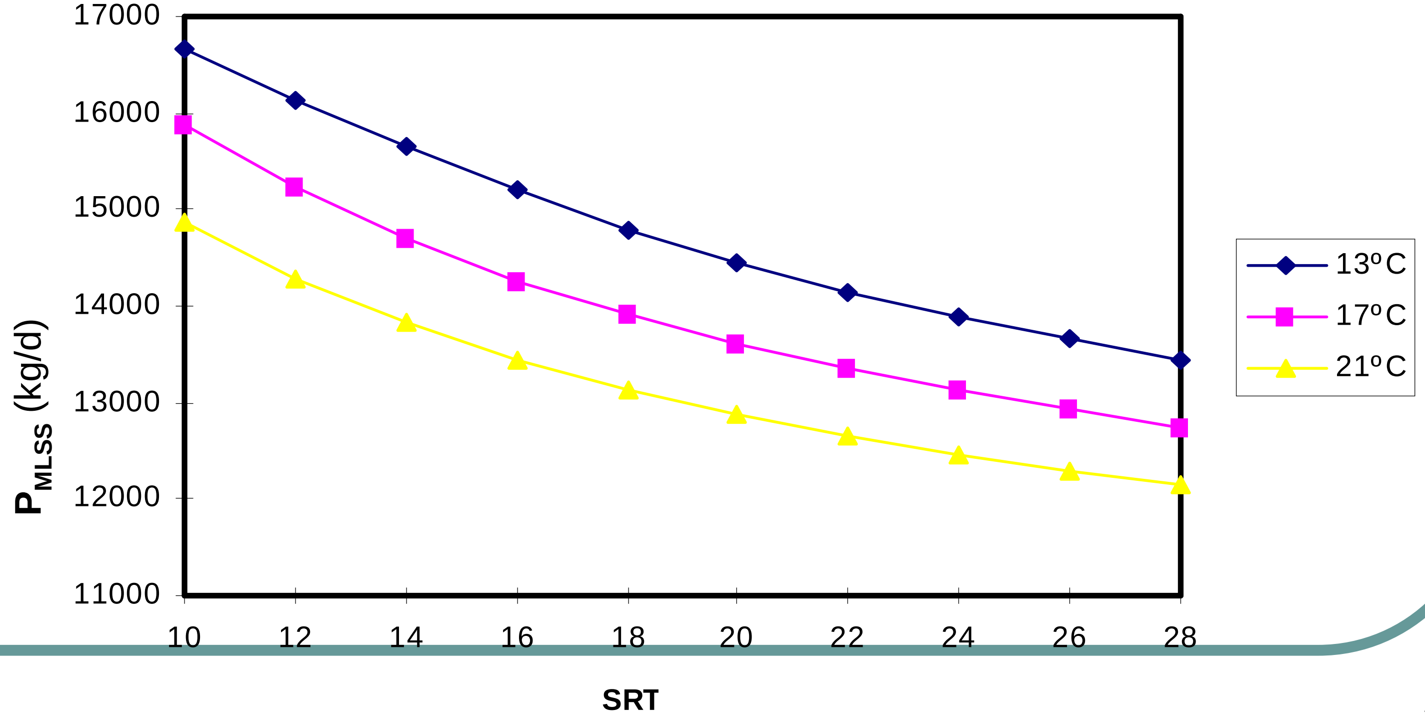


Operational variables

Wastage Rate: Solids Retention Time

Influence of SRT in Sludge Production

- Very significant influence
- Relevant for the operation costs (sludge handling)



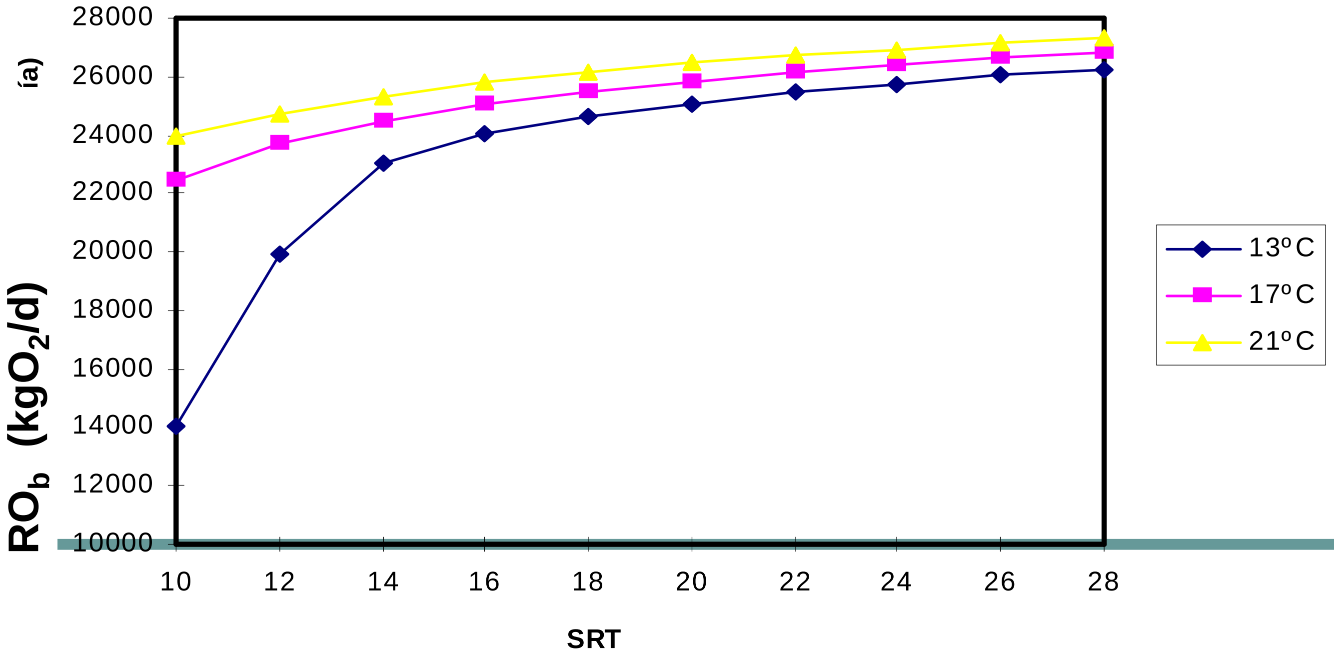
Operational variables

Wastage Rate: Solids Retention Time

Influence of SRT in O_2 requirements

Increase of oxygen requirements (endogenous respiration)

For low SRT the reduction in oxygen requirements is associated to deterioration of effluent quality



Operational variables

Sludge Recirculation

1- Objective

- Regulation of the sludge mass in the settler and maintain enough biomass in the process

2- Effects

- Low influence in the biological processes
- Significant influence in effluent quality (solids)

3- Operational restrictions

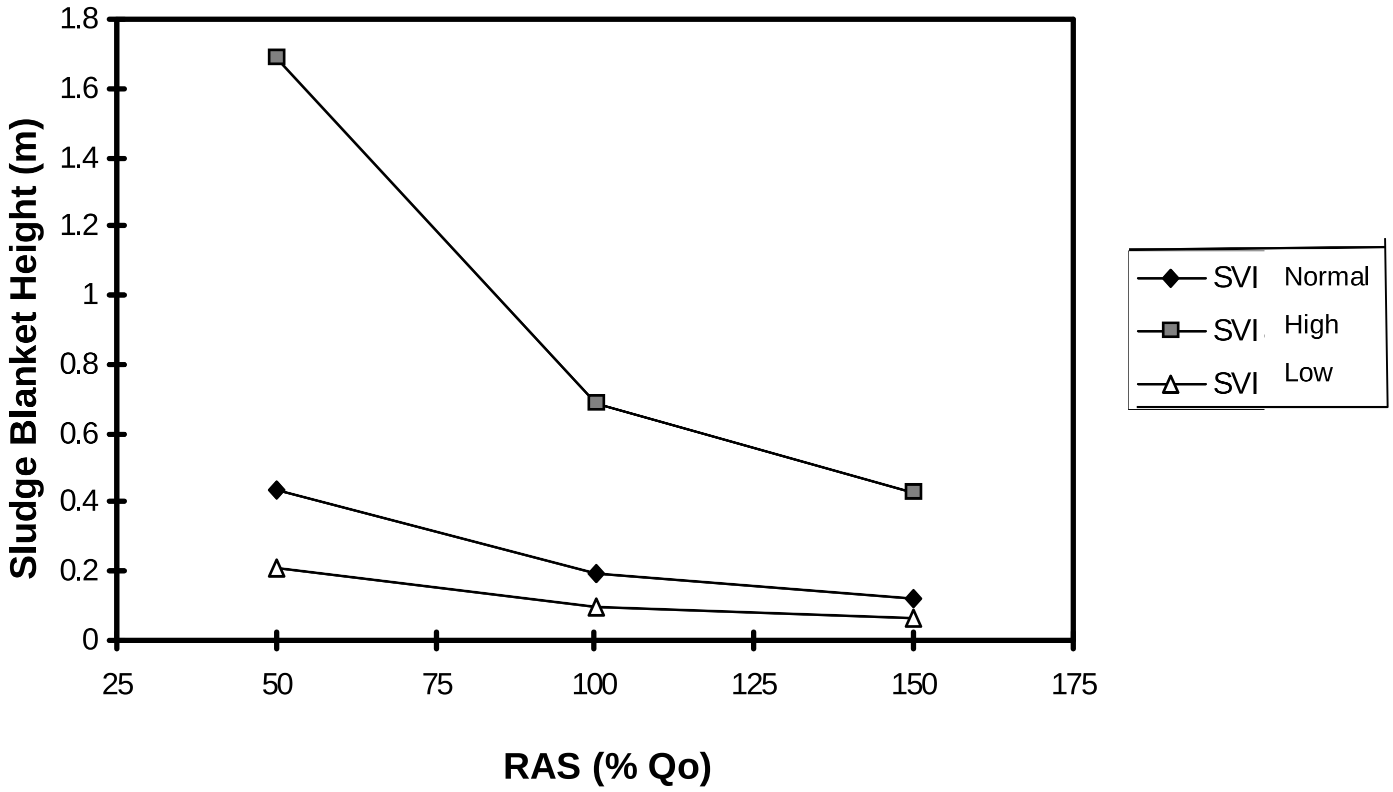
- Sludge blanket height
- Retention time of the settled sludge
- Hydraulic perturbations in the clarification
- Dilution of the sludge

4- Conventional operation

- Constant flow
- Flow proportional to the influent
- Regulation of the sludge blanket height

Operational variables

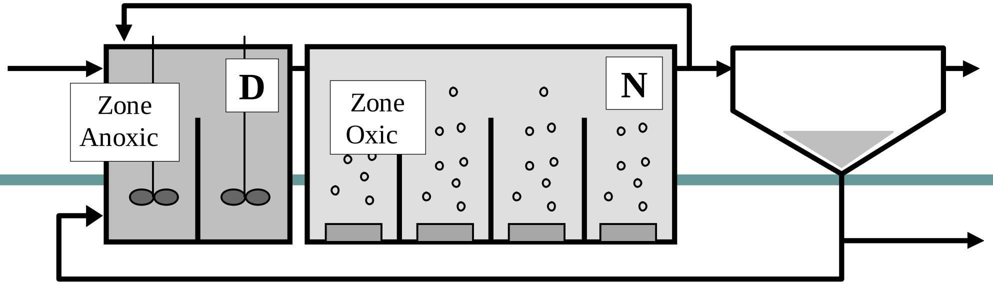
Sludge Recirculation



Operational variables

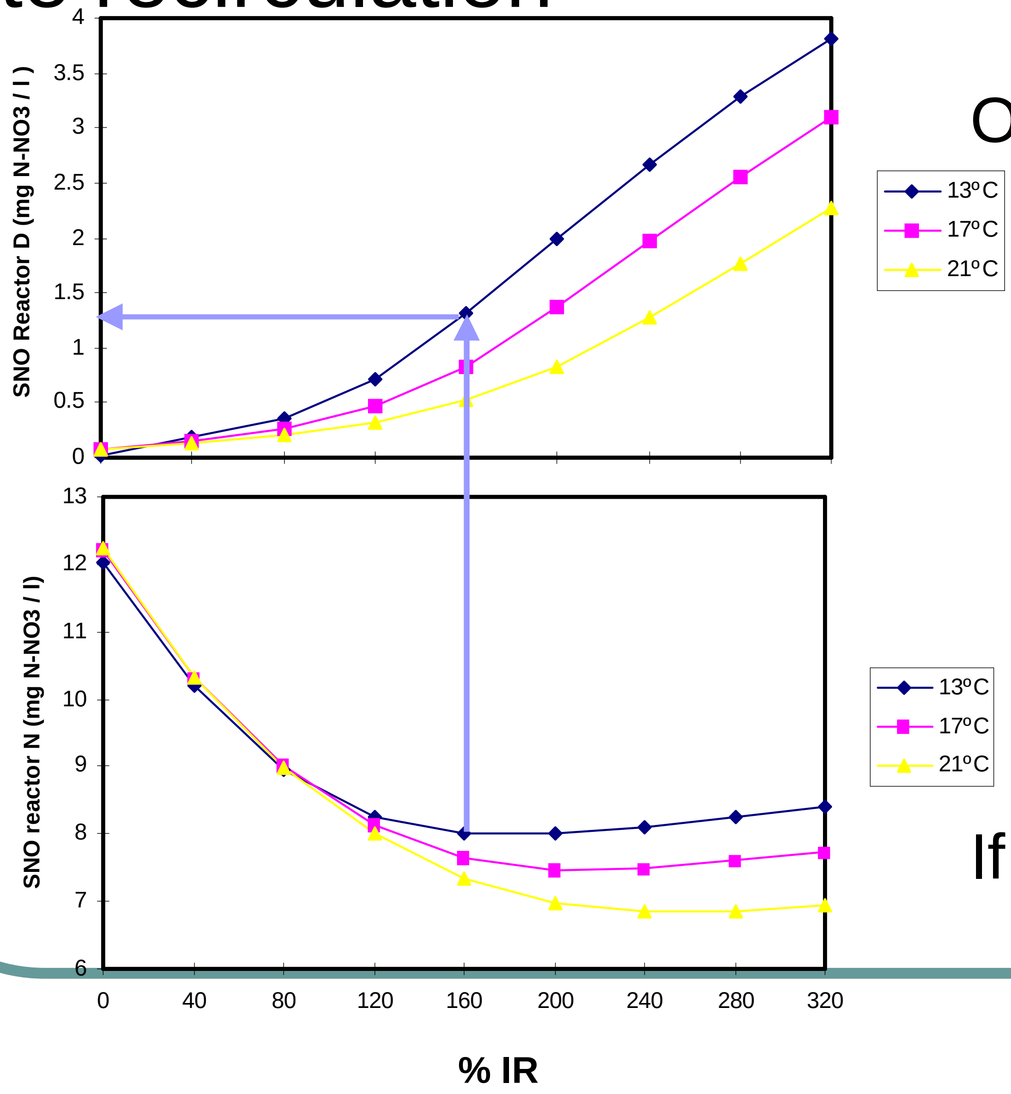
Nitrate Recirculation

- Objective
  - Supply Nitrates to the anoxic zones for denitrification
- Operational restrictions
  - Flow high enough to supply Nitrates for denitrification
  - Avoid inhibition of the denitrification for excess of oxygen
  - Optimal recirculation depends at each moment on the operational conditions and influent load
- Conventional operation
  - Flow proportional to the influent



Operational variables

Nitrate recirculation



Optimum point: minimum [nitrate] in the effluent

- Minimum is variable
- Nitrates in D constant

If this optimum point is not good enough:

- External addition of C

Operational variables

Aeration

1- Objective

- Supply DO for maintaining the activity in the aerobic process

2- Operational restrictions

- Air Flow high enough to maintain DO and solids in suspension
  (low DO reduces biological activity in aerobic processes)
- Avoid excess of aeration:
  - No proportional increment in the biological activity
  - Increase the operational expenses (O_2 emitted to the atmosphere)
  - Risk of excess of stirring intensity → floc damage
- Important point: efficiency in oxygen transfer to the water

3- Conventional operation

- Constant DO_{SP} = 2.0 mg/l

Operational variables

Aeration

Oxygen consumption

- Associated with biological oxidation of COD and Ammonium & endogenous activity
- Oxygen requirements can not be reduced without affecting water quality in the effluent
- Optimum use of denitrification minimize O_2 requirements

Oxygen supply

- Supplied by air flow (K_La) with an efficiency regulated by the distance to saturation (DO_{SAT}-DO)
- Maximum efficiency at minimum DO concentration
- But low DO concentration reduces biological activity

$$\frac{dOD}{dt} = \frac{Q}{V}(OD_e - OD) + K_L a(OD_{SAT} - OD) - OUR$$

Operational variables

Aeration

Optimum operation:

- How to supply required DO with minimum air flow?
- Minimum (constant) DO that guarantees ammonium requirements in the effluent
- It includes some kind of “predictive” strategy (repeatability in the influent load profile)