

4

Organic matter removal

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4.1 INTRODUCTION

Chapter 4 on Organic Matter Removal in the textbook *Biological Wastewater Treatment: Principles, Modelling and Design* (Chen *et al.*, 2020) introduces the principles behind the physical, chemical and microbial conversions and key factors affecting the removal of organic matter in activated sludge systems. It provides the basis to understand the mechanisms involved in the removal of organic matter and presents a stoichiometric-based steady-state model for the design of activated sludge systems that carry out most of the aerobic removal of organic matter. The present chapter aims to guide the reader through the principles, microbial mechanisms and the steady-state stoichiometric model to design, assess and evaluate conventional activated sludge (CAS) wastewater treatment systems. All the equations presented here belong to the textbook.

4.2 LEARNING OBJECTIVES

After the successful completion of this chapter, the reader will be able to:

- Describe the basic transformations of organic and inorganic wastewater compounds that take place in CAS wastewater treatment plants.
- Discuss the fundamental principles for the selection, design and control of the sludge age of activated sludge wastewater treatment systems.
- Describe and assess the influence of key system constraints, environmental factors and operational parameters on the performance of CAS wastewater treatment plants.
- Apply a stoichiometric-based steady-state model for the process design and evaluation of activated sludge wastewater treatment plants performing the aerobic removal of organic matter.
- Explain the meaning of the food-to-microorganism ratio and its applicability within the context of the COD stoichiometric-based steady-state model for the process design of CAS wastewater treatment plants.

4.3 EXAMPLES

Example 4.3.1

By applying the COD stoichiometric-based steady-state design model, design an activated sludge system (Figure 4.1) to treat an influent wastewater (Q_i) with a flow rate of 15 MLD (15,000 m³/d). The plant needs to comply with an effluent total COD concentration (COD_e) of 125 mg COD/l. The plant does not have a primary settling tank. The raw wastewater contains a total influent COD concentration (COD_i) of 585 mg/l that contains an influent total Kjeldahl nitrogen concentration (TKN_i) and total phosphorus concentration (P_i) of 44.5 mgN/l and 14.5 mgP/l, respectively. The influent COD fractionation is shown in Figure 4.2. In addition, the influent flow rate contains 35 mg/l of inorganic or fixed suspended solids.

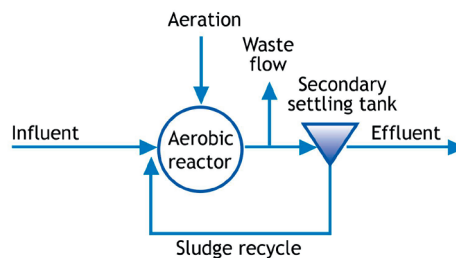


Figure 4.1 Activated sludge system with a single reactor completely-mixing regime.

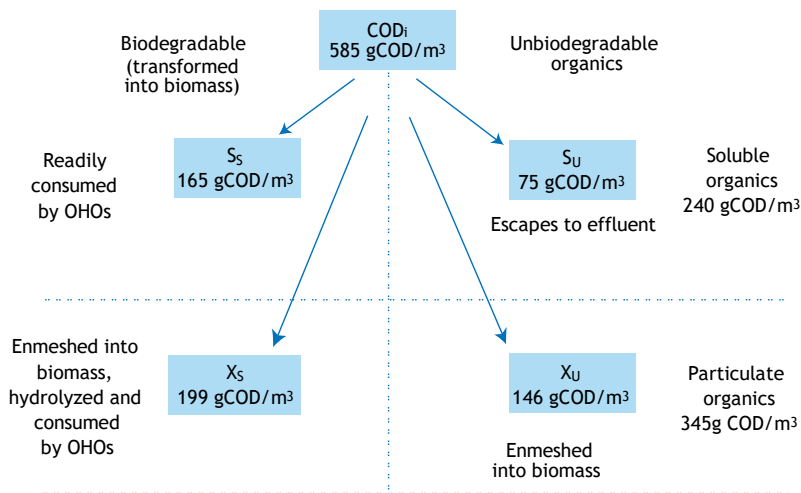


Figure 4.2 Influent COD fractionation for the activated sludge design example 4.3.1.

To carry out the design, assume:

- A minimum yearly wastewater temperature of 14 °C.
- An SRT of 6 days.
- An average MLSS concentration of 4,000 mg/l to size the aerobic reactor volume (V_R).
- A TSS concentration in the effluent of the secondary settling tank of 15 mgTSS/l.
- A TSS concentration in the sludge recycle flow of 10,000 mgTSS/l.

Based on the previous information, determine:

- The s-recycle ratio required to keep an average MLSS concentration of 4,000 mgTSS/l in the system ($s = Q_s/Q_i$; where Q_s is the sludge recycle flow rate and Q_i is the influent flow rate).
- Total COD flux consumed by OHO.
- MX_{VSS} and MX_{TSS} masses.
- Total volume of the system (V_R)
- Nutrient requirement of the system (N_s and P_s).
- O_2 requirements of the system.
- Effluent total COD, total Kjeldahl nitrogen and total phosphorus concentrations (COD_e , TKN_e and P_e , respectively).
- The COD mass balance in order to confirm the reliability of your design.

Solution

Table 4.1 presents a summary of the main design data and Table 4.2 displays the main stoichiometric and kinetic parameters necessary to carry out the process design.

Table 4.1 Summary of the data to carry out the process design of the activated sludge plant.

Description	Symbol	Value	Unit
Flow rate	Q_i	15	MLD
Total COD	COD_i	585	gCOD/m ³
COD concentrations			
- readily biodegradable COD	$S_{S,i}$	165	gCOD/m ³
- slowly biodegradable COD	$X_{S,i}$	199	gCOD/m ³
- unbiodegradable soluble COD	$S_{U,i}$	75	gCOD/m ³
- unbiodegradable particulate COD	$X_{U,i}$	146	gCOD/m ³
Influent inorganic (fixed) suspended solids	$X_{FSS,i}$	35	gFSS/m ³
Influent TKN concentration	TKN_i	44.5	gN/m ³
Influent total P concentration	P_i	14.5	gP/m ³
Temperature	T	14	°C
Sludge retention time	SRT	6	d
Total suspended solids in the effluent	$X_{TSS,e}$	15	gTSS/m ³
Design TSS concentration	X_{TSS}	4,000	gTSS/m ³

Table 4.2 Kinetic and stoichiometric parameters for the EBPR design example 4.3.1.

Parameter	Symbol	Value	Unit
<i>OHO</i>			
Kinetic	Specific endogenous mass loss rate of the OHOs at 20 °C	$b_{\text{OHO},20}$	0.24 gVSS /gVSS.d
	Temperature coefficient for $b_{\text{OHO},T}$	$\theta_{b,\text{OHO}}$	1.029
	Specific endogenous mass loss rate of the OHOs at temperature T	$b_{\text{OHO},T}$	0.202 gVSS /gVSS.d
<i>OHO</i>			
Stoichiometric	Biomass yield of the OHOs	$Y_{\text{OHO},v}$	0.45 gVSS/gCOD
	Fraction of endogenous residue of the OHOs	$f_{\text{XE},\text{OHO}}$	0.20 gVSS/gVSS
	Fraction of fixed (inorganic) suspended solids of the OHOs	$f_{\text{FSS},\text{OHO}}$	0.15 gFSS/gVSS
	<i>General</i>		
	COD/VSS ratio of the sludge	f_{cv}	1.48 gCOD/gVSS
	Nitrogen content in the volatile suspended solids	f_{n}	0.10 gN/gVSS
	Phosphorus content in the volatile suspended solids	f_{p}	0.03 gP/gVSS

Using the data provided, Table 4.3 shows the detailed calculations to carry out the process design to comply with COD_e of less than 125 mg/l.

Table 4.3 Activated sludge system design procedure.

1. System configuration			
Aerobic completely-stirred tank reactor configuration operated at 14 °C			
2. Influent and sludge recycle composition (based on table 4.1 and figure 4.2)			
Q_i	15	MLD	(15,000 m ³ /d) influent flow rate
2.1 Influent concentrations			
<i>Influent and bioreactor data</i>			
COD_i	585	gCOD/m ³	influent concentration of total COD
$\text{SS}_{s,i}$	165	gCOD/m ³	influent concentration of readily biodegradable COD
$\text{X}_{\text{S},i}$	199	gCOD/m ³	influent concentration of slowly biodegradable COD
$\text{COD}_{\text{b},i}$	364	gCOD/m ³	influent concentration of biodegradable COD ($\text{SS}_{s,i} + \text{X}_{\text{S},i}$)
$\text{S}_{\text{U},i}$	75	gCOD/m ³	influent concentration of soluble unbiodegradable COD
$\text{X}_{\text{U},i}$	146	gCOD/m ³	influent concentration of particulate unbiodegradable COD
$\text{X}_{\text{FSS},i}$	35	gFSS/m ³	influent concentration of fixed (inorganic) suspended solids
TKN_i	44.5	gN/m ³	influent concentration of total Kjeldahl N
P_i	14.5	gP/m ³	influent concentration of total P

2.2 Influent flux used for calculations (= $Q_i \cdot$ influent concentration of component)

$FCOD_i$	8,775	kgCOD/d	influent daily flux of total COD
$FS_{s,i}$	2,475	kgCOD/d	influent daily flux of RBCOD
$FCOD_{b,i}$	5,460	kgCOD/d	influent daily flux of biodegradable COD ($SS_{s,i} + X_{s,i}$)
$FX_{U,i}$	2,190	kgCOD/d	influent daily flux of particulate unbiodegradable COD
$FS_{U,i}$	1,125	kgCOD/d	influent daily flux of soluble unbiodegradable COD
$FX_{FSS,i}$	525	kgFSS/d	influent daily flux of fixed (inorganic) suspended solids

2.3 Sludge recycle characteristics

s		$m^3.d / m^3.d$	$s = X_{TSS} / (X_{TSS,s} - X_{TSS})$
		$m^3.d / m^3.d$	$s = 4,000 / (10,000 - 4,000)$
s	0.67	$m^3.d / m^3.d$	sludge recycle ratio (s) with regard to influent flow rate

3. Biomass equations

Corresponds to the biological mass present in the system as synthesized from the influent COD (in g/d), taking into account the cumulative effect of SRT [(g/d) · d = g in the system]

3.1 OHOs

Active mass

$$\begin{aligned}
 Y_{OHOv} &= 0.45 \text{ gVSS/gCOD} \\
 Y_{OHOv,obs} &= Y_{OHOv} / (1 + b_{OHO,T} \cdot SRT) \\
 &= 0.45 / (1 + 0.202 \cdot 6) \\
 Y_{OHOv,obs} &= 0.203 \text{ gVSS/gCOD} \\
 MX_{OHOv} &= Y_{OHOv,obs} \cdot FCOD_{b,i} \cdot SRT \\
 &= 0.203 \cdot 5,460 \cdot 6 \\
 MX_{OHOv} &= 6,661 \text{ kgVSS}
 \end{aligned} \tag{4.9}$$

Endogenous mass

$$\begin{aligned}
 MX_{E,OHOv} &= f_{XE,OHO} \cdot b_{OHO,T} \cdot MX_{OHOv} \cdot SRT \\
 &= 0.20 \cdot 0.202 \cdot 6,661 \cdot 6 \\
 MX_{E,OHOv} &= 1,616 \text{ kgVSS}
 \end{aligned} \tag{4.10}$$

3.2 Unbiodegradable particulate organics

$$\begin{aligned}
 MX_{Uv} &= FX_{U,i} \cdot SRT / f_{cv} \\
 &= 2,190 \cdot 6 / 1.48 \\
 MX_{Uv} &= 8,878 \text{ kgVSS}
 \end{aligned} \tag{4.11}$$

4. VSS and TSS

4.1 VSS and active fraction

$$\begin{aligned}
 MX_B &= MX_{OHOv} \\
 MX_B &= 6,661 \text{ kgVSS}
 \end{aligned}$$

$$\begin{aligned}
 MX_{VSS} &= MX_{OHOv} + MX_{E,OHOv} + MX_{Uv} \\
 &= 6,661 + 1,616 + 8,878
 \end{aligned}
 \quad (4.12)$$

$$\begin{aligned}
 MX_{VSS} &17,156 \text{ kgVSS} \\
 f_{av} &= MX_B / MX_{VSS} \\
 &= 6,661 / 17,156
 \end{aligned}$$

$$f_{av} = 39 \%$$

4.2 FSS

$$\begin{aligned}
 MX_{FSS} &= f_{FSS,OHO} \cdot MX_{OHOv} + FX_{FSS,i} \cdot SRT \\
 &= (0.15 \cdot 6,661) + (525 \cdot 6)
 \end{aligned}
 \quad (4.14a)$$

$$MX_{FSS} = 4,149 \text{ kgFSS}$$

4.3 TSS

$$\begin{aligned}
 MX_{TSS} &= MX_{VSS} + MX_{FSS} \\
 &= 17,156 + 4,149
 \end{aligned}
 \quad (4.15)$$

$$MX_{TSS} = 21,305 \text{ kgTSS}$$

4.4 f_{VT}

$$\begin{aligned}
 f_{VT} &= MX_{VSS} / MX_{TSS} \\
 &= 17,156 / 21,305
 \end{aligned}
 \quad (4.16)$$

$$f_{VT} = 0.81 \text{ gVSS/gTSS}$$

5. Process volume (based on TSS)

$$X_{TSS} = 4 \text{ kgTSS} / \text{m}^3$$

$$\begin{aligned}
 V_R &= MX_{TSS} / X_{TSS} \\
 &= 21,305/4
 \end{aligned}
 \quad (4.20)$$

$$V_R = 5,326 \text{ m}^3$$

6. Nutrient requirements

6.1 Nitrogen requirements for biomass synthesis

$$\begin{aligned}
 N_s &= f_n \cdot MX_{VSS} / (Q_i SRT) \\
 &= (0.10 \cdot 17,156) / (15 \cdot 6)
 \end{aligned}
 \quad (5.25)$$

$$N_s = 19.1 \text{ gN/m}^3$$

6.2 Phosphorus requirements for biomass synthesis

$$\begin{aligned}
 P_s &= f_p \cdot MX_{VSS} / (Q_i SRT) \\
 &= (0.03 \cdot 17,156) / (15 \cdot 6)
 \end{aligned}$$

$$P_s = 5.7 \text{ gP/ m}^3 \quad (5.31)$$

7. Oxygen demand (OD)

OD for synthesis and endogenous respiration

$$FO_{OHO} = FO_{OHO,s} + FO_{OHO,e} \quad (6.30a)$$

$$FO_{OHO,s} = F_{COD_{b,OHO}} \cdot (1 - f_{cv} \cdot Y_{OHOv})$$

$$\begin{aligned}
 &= 5,460 \cdot (1 - 1.48 \cdot 0.45) \\
 FO_{OHO,s} &1,824 \\
 FO_{OHO,e} &= F_{COD,b,OHO} \cdot f_{cv} \cdot (1 - f_{XE,OHO}) \cdot b_{OHO,T} \cdot Y_{OHOv,obs} \cdot SRT \\
 &= 5,460 \cdot 1.48 \cdot (1 - 0.20) \cdot 0.202 \cdot 0.203 \cdot 6 \\
 FO_{OHO,e} &1,595 \\
 FO_{OHO} &3,418 \text{ kgO}_2/\text{d}
 \end{aligned}$$

8. Effluent quality

8.1 COD_e

$$\begin{aligned}
 COD_e &= S_{U,i} + f_{cv} \cdot f_{VT} \cdot X_{TSS,e} && \text{(non-filtered)} \\
 &= 75 + (1.48) \cdot (0.81) \cdot (15) \\
 &93 \text{ gCOD/m}^3
 \end{aligned}$$

8.2 TKN_e

$$\begin{aligned}
 TKN_e &= TKN_i - N_s + f_n \cdot f_{VT} \cdot X_{TSS,e} && \text{(non-filtered)} \\
 &= 44.5 - 19.1 + (0.10) \cdot (0.81) \cdot (15) \\
 &26.6 \text{ gN/m}^3
 \end{aligned}$$

8.3 P_e

$$\begin{aligned}
 P_e &= P_i - P_s + f_p \cdot f_{VT} \cdot X_{TSS,e} && \text{(non-filtered)} \\
 &= 14.5 - 5.7 + (0.03) \cdot (0.81) \cdot (15) \\
 &9.2 \text{ gP/m}^3
 \end{aligned}$$

Overall, the system is able to comply with the effluent total COD discharge limit of 125 mgCOD/l. It also produces a treated effluent that contains a total Kjeldahl concentration of 26.6 mgN/l and total phosphorus concentration of 9.2 mgP/l. This indicates that despite the system not being designed for nutrient removal, it is able to remove approximately 40 % and 37 % of the nitrogen and phosphorus concentrations present in the influent wastewater, respectively. It is important to underline that these effluent concentrations have been estimated based on the effluent TSS concentration being 15 mgTSS/l. If the effluent TSS is different, then other concentrations can be expected.

9. Waste of activated sludge

$$\begin{aligned}
 Q_w &= V_R/SRT && (4.1) \\
 &= 5,326/6 \\
 Q_w &888 \text{ m}^3/\text{d}
 \end{aligned}$$

10. COD mass balance verification

Input

FCOD _i	8,775	kgCOD/d	100 %	IN
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Output

O₂ demand for synthesis and endogenous respiration of OHO (FO_{OHO} = FO_e)

FO _e	3,418	kgCOD/d	39.0 %
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Soluble unbiodegradable organics leaving via the effluent

FS _{U,i}	1,125	kgCOD/d	12.8 %
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Sludge	gVSS	kgCOD/d		
		$(= \text{gVSS} \cdot f_{cv} / \text{SRT} = \text{gVSS} \cdot 1.48 / 8 = \text{gVSS} \cdot 0.185)$		
$\text{MX}_{\text{OHOv}} (= \text{MX}_B)$	6,661	1,643	kgCOD/d	18.7 %
$\text{MX}_{\text{E,OHOv}}$	1,616	399	kgCOD/d	4.5 %
MX_{Uv}	8,878	2,190	kgCOD/d	25.0 %
$\text{MX}_{\text{E,OHO}} + \text{MX}_{\text{Uv}}$	10,494	2,589		29.5 %
MX_{VSS}	17,156	4,232	kgCOD/d	48.2 %
Sum:		8,775	kgCOD/d	100 %
Delta (OUT-IN):		0	kgCOD/d	0 %

OUT

The 100 % mass balance for COD indicates that all the influent COD is accounted for in the calculated values of oxygen demand and sludge production. From the COD mass balance, and for the conditions of the design example, the fate of the influent COD is as follows: 39 % is oxidized with oxygen, 12.8 % escapes in the effluent as soluble unbiodegradable organics and 48.2 % becomes activated sludge. This activated sludge is composed of 38.8 % (6,661 / 17,156) active biomass and 61.1% (10,494 / 17,156) inactive particulate matter of which 84.6 % (8,878 / 10,494) are influent unbiodegradable particulate organics and 15.4 % (1,616 / 10,494) is endogenous residue). A summary of the process design results is presented in Table 4.4.

Table 4.4 Summary of the process design results.

Description	Parameter	Unit	Value
1. Influent and bioreactor			
Type of wastewater	Raw		raw
Temperature	T	°C	14
Influent flow rate	Q_i	MLD	15
Influent total COD	COD_i	gCOD/m ³	585
Influent biodegradable COD	$\text{COD}_{b,i}$	gCOD/m ³	364
Influent TKN	TKN_i	gN/m ³	44.5
Influent total P	P_i	gP/m ³	14.5
Sludge retention time	SRT	d	6
Sludge recycle ratio (s)	s	m ³ .d / m ³ .d	0.67
2. $\text{COD}_{b,i}$ for OHOs			
Flux of $\text{COD}_{b,i}$ for OHOs	$\text{FCOD}_{b,\text{OHO}}$	kgCOD/d	5,460
3. System biomass (VSS) equations			
Mass of OHOs	MX_{OHOv}	kgVSS	6,661
Mass of endogenous residue from OHOs	$\text{MX}_{\text{E,OHOv}}$	kgVSS	1,616
Mass of unbiodegradable organics from influent	MX_{Uv}	kgVSS	8,878
4. Volatile and total suspended solids (VSS and TSS) in system			
Mass of active biomass (= MX_{OHOv})	MX_B	kgVSS	6,661
Mass of VSS	MX_{VSS}	kgVSS	17,156
MX_B/VSS	f_{av}	gVSS/gVSS	0.39

Mass of fixed or inorganic SS	MX_{FSS}	kgFSS	4,149
Mass of TSS	MX_{TSS}	kgTSS	21,305
Ratio of VSS/TSS	f_{VT}	gVSS/gTSS	0.81
5. Reactor volume			
Bioreactor volume	V_R	m ³	5,326
6. Waste of activated sludge			
Activated sludge waste flow rate	Q_W	m ³ /d	888
7. Nutrient requirement			
N requirement concentration for biomass synthesis	N_s	gN/m ³	19.1
P requirement concentration for biomass synthesis	P_s	gP/m ³	5.7
8. Oxygen demand			
Flux of carbonaceous O ₂ demand	FO_C	kgO ₂ /d	3,418
9. Treated effluent quality ^{a)}			
Effluent total COD	COD_e	gCOD/m ³	93.0
Effluent total Kjeldahl Nitrogen	TKN_e	gN/m ³	26.6
Effluent total phosphorus	P_e	gP/m ³	9.2
10. COD mass balance			
COD output/COD input	COD mass balance	gCOD/gCOD	100 %

Flow rate is in m³/d and mass fluxes in kg/d

For a flow rate of 1,000 or greater, mass fluxes can be read in kg/d

^{a)} Considering an effluent total solids concentration of 15 mgTSS/l.

Example 4.3.2

Design the activated sludge plant designed in Example 4.3.1 following the food-to-microorganism (F/M) ratio.

Table 4.5 Activated sludge system design procedure following the F/M ratio approach (using the same data from Example 4.3.1).

1. System configuration			
Aerobic completely-stirred tank reactor configuration process configuration operated at 14 °C			
2. Influent composition (from previous example 4.3.1)			
Q_i	15	MLD	(15,000 m ³ /d) influent flow rate
COD_i	585	gCOD/m ³	influent concentration of total COD
$S_{U,i}$	75	gCOD/m ³	influent concentration of soluble unbiodegradable COD
$f_{S,U,CODi}$	$= S_{U,i} / COD_i$ $= 75/585$	gCOD/gCOD	influent fraction of soluble unbiodegradable COD
$f_{S,U,CODi}$	0.13	gCOD/gCOD	influent fraction of soluble unbiodegradable COD
$X_{U,i}$	146	gCOD/m ³	influent concentration of particulate unbiodegradable COD
$f_{X,U,CODi}$	$= X_{U,i} / COD_i$	gCOD/gCOD	influent fraction of particulate unbiodegradable COD
$f_{X,U,CODi}$	$= 146/585$		

$f_{XU,CODi}$	0.25	gCOD/gCOD	influent fraction of particulate unbiodegradable COD
$X_{FSS,i}$	35	gFSS/m ³	influent concentration of fixed (inorganic) suspended solids

3. Determination of $A_{ND,TSS}$ ratio

$$A_{ND} = (1 - f_{SU,CODi} - f_{XU,CODi}) \cdot [Y_{OH,O} \cdot SRT / (1 + b_{OH,O,T} \cdot SRT)] \cdot [1 + f_{XE,OHO} \cdot b_{OH,O,T} \cdot SRT + f_{FSS,OHO}] + [(f_{XU,CODi} / f_{cv}) + (X_{FSS,i} / COD_i)] \cdot SRT \quad (4.35)$$

$$= (1 - 0.13 - 0.25) \cdot [(0.45 \cdot 6) / (1 + (0.202 \cdot 6))] \cdot [1 + (0.20 \cdot 0.202 \cdot 6) + 0.15] + [(0.25 / 1.48) + (35 / 585)] \cdot 6$$

$$A_{ND} = 2.43 \text{ kgTSS/kgCOD.d}$$

Since:

$$A_{ND} = 1 / (F/M)_{COD,TSS}$$

$$(F/M)_{COD,TSS} = 1 / A_{ND}$$

$$= 1 / 2.43$$

$$(F/M)_{COD,TSS} = 0.41 \text{ kgCOD.d/kgTSS}$$

4. Reactor volume

$$(F/M)_{COD,TSS} = Q_i \cdot COD_i / V_R \cdot X_{TSS} \quad (\text{derived from 4.36a})$$

Then:

$$V_R = Q_i \cdot COD_i / (X_{TSS} \cdot (F/M)_{COD,TSS})$$

Thus:

$$V_R = Q_i \cdot COD_i / (X_{TSS} \cdot (F/M)_{COD,TSS})$$

$$\text{Since } X_{TSS} = 4 \text{ kgTSS/m}^3$$

$$= (15 \cdot 585) / (4 \cdot 0.41)$$

$$V_R = 5,321 \text{ m}^3$$

The volume of the reactor is the same as that obtained using the stoichiometric-based design model. This indicates that the two procedures can lead to similar results. Furthermore, the F/M ratio of 0.41 kgCOD.d/kgVSS indicates that it is a high-rate system and, with the SRT of 6d, it only performs the removal of COD (see Figure 4.8 in *Chen et al.*, 2020).

Example 4.3.3

The activated sludge plant designed in Example 4.3.1 only carries out the COD removal process. However, based on the MX_B / MX_{TSS} and f_{VT} ratios (of 0.39 and 0.81, respectively), the system generates an activated sludge waste flow rate of 888 m³/d that contains a considerable fraction of active biomass (see Table 4.4 in Example 4.3.1). This sludge needs to be properly handled (digested either aerobically or preferably anaerobically) prior to dewatering and disposal. As such, the purpose is to redesign the plant with a longer SRT that should be long enough to decrease the fraction of the active biomass (e.g., to design an extended aeration activated sludge system).

Based on the previous requirements, the system will be designed with an SRT of 25 days. Using the data provided, Table 4.6 shows the detailed calculations to carry out the process design to decrease the active mass fraction and generate stable activated sludge waste.

Table 4.6 Procedure for the design of an activated sludge system designed with a long SRT (extended aeration system).

1. System configuration			
Aerobic completely-stirred tank reactor configuration process configuration operated at 14 °C			
2. Influent and sludge recycle composition (from previous tables)			
Q_i	15	MLD	(15,000 m ³ /d) influent flow rate
2.1 Influent concentrations			
<i>Influent and bioreactor data</i>			
COD _i	585	gCOD/m ³	influent concentration of total COD
SS _{s,i}	165	gCOD/m ³	influent concentration of readily biodegradable COD
X _{S,i}	199	gCOD/m ³	influent concentration of slowly biodegradable COD
COD _{b,i}	364	gCOD/m ³	influent concentration of biodegradable COD (SS _{s,i} + X _{S,i})
S _{U,i}	75	gCOD/m ³	influent concentration of soluble unbiodegradable COD
X _{U,i}	146	gCOD/m ³	influent concentration of particulate unbiodegradable COD
X _{FSS,i}	35	gFSS/m ³	influent concentration of fixed (inorganic) suspended solids
TKN _i	44.5	gN/m ³	influent concentration of total Kjeldahl N
P _i	14.5	gP/m ³	influent concentration of total P
2.2 Influent fluxes used for calculations (= $Q_i \cdot$ influent concentration of component)			
FCOD _i	8,775	kgCOD/d	influent daily flux of total COD
FSS _{s,i}	2,475	kgCOD/d	influent daily flux of RBCOD
FCOD _{b,i}	5,460	kgCOD/d	influent daily flux of biodegradable COD (SS _{s,i} + X _{S,i})
FX _{U,i}	2,190	kgCOD/d	influent daily flux of particulate unbiodegradable COD
FS _{U,i}	1,125	kgCOD/d	influent daily flux of soluble unbiodegradable COD
FX _{FSS,i}	525	kgFSS/d	influent daily flux of fixed (inorganic) suspended solids
2.3 Sludge recycle characteristics			
s		m ³ .d/ m ³ .d	$s = X_{TSS} / (X_{TSS,s} - X_{TSS})$
		m ³ .d/ m ³ .d	$s = 4,000 / (10,000 - 4,000)$
s	0.67	m ³ .d/ m ³ .d	sludge recycle ratio (s) with regard to influent flow rate
3. Biomass equations			
Corresponds to the biological mass present in the system as synthesized from the influent COD (in g/d), taking into account the cumulative effect of SRT [(g/d) · d = g in the system]			
3.1 OHOs			
Active mass			
Y _{OHOv}	0.45 gVSS/gCOD		
Y _{OHOv,obs}	$= Y_{OHOv} / (1 + b_{OHO,T} \cdot SRT)$ $= 0.45 / (1 + 0.202 \cdot 25)$		
Y _{OHOv,obs}	0.074 gVSS/gCOD		

$$\begin{aligned}
MX_{OHOv} &= Y_{OHOv,obs} \cdot F_{CODb,i} \cdot SRT \\
&= 0.074 \cdot 5,460 \cdot 25 \\
MX_{OHOv} &10,156 \text{ kgVSS} \\
\text{Endogenous mass} \\
MX_{E,OHOv} &= f_{XE,OHO} \cdot b_{OHO,T} \cdot MX_{OHOv} \cdot SRT \\
&= 0.20 \cdot 0.202 \cdot 10,156 \cdot 25 \\
MX_{E,OHOv} &10,256 \text{ kgVSS}
\end{aligned} \tag{4.10}$$

3.2 Unbiodegradable particulate organics

$$\begin{aligned}
MX_{Uv} &= FX_{U,i} \cdot SRT / f_{cv} \\
&= 2,190 \cdot 25 / 1.48 \\
MX_{Uv} &36,993 \text{ kgVSS}
\end{aligned} \tag{4.11}$$

4. VSS and TSS

4.1 VSS and active fraction

$$\begin{aligned}
MX_B &= MX_{OHOv} \\
MX_B &10,156 \text{ kgVSS} \\
MX_{VSS} &= MX_{OHOv} + MX_{E,OHOv} + MX_{Uv} \\
&= 10,156 + 10,256 + 36,993 \\
MX_{VSS} &57,405 \text{ kgVSS} \\
f_{av} &= MX_B / MX_{VSS} \\
&= 10,156 / 57,405 \\
f_{av} &18 \%
\end{aligned} \tag{4.12}$$

With the SRT of 25 days, the active mass fraction comprises 18 % of MX_{VSS} , indicating that the sludge can be considered to be stabilized (assumed to happen when $f_{bio,VSS} < 20 \%$).

4.2 FSS

$$\begin{aligned}
MX_{FSS} &= f_{FSS,OHO} \cdot MX_{OHOv} + FX_{FSS,i} \cdot SRT \\
&= (0.15 \cdot 10,156) + (525 \cdot 25) \\
MX_{FSS} &14,648 \text{ kgFSS}
\end{aligned} \tag{4.14a}$$

4.3 TSS

$$\begin{aligned}
MX_{TSS} &= MX_{VSS} + MX_{FSS} \\
&= 57,405 + 14,648 \\
MX_{TSS} &72,053 \text{ kgTSS}
\end{aligned} \tag{4.15}$$

4.4 f_{VT}

$$\begin{aligned}
f_{VT} &= MX_{VSS} / MX_{TSS} \\
&= 57,405 / 72,053 \\
f_{VT} &0.80 \text{ gVSS/gTSS}
\end{aligned} \tag{4.16}$$

In spite of the long SRT of 25 days, the f_{VT} ratio remains similar to that of the design carried out with SRT of 6 days. The main reason is that, at the extended SRT of 25 d, less active biomass is produced per COD consumed (the $Y_{OHOv,obs}$ decreases from 0.203 to 0.074 kgVSS/kgCOD as the SRT increases from 6 to 25 d). However, simultaneously, the longer SRT also causes a proportionally higher generation and accumulation of the endogenous residue mass ($MX_{E,OHOv}$). This results in a relatively constant f_{VT} ratio regardless of the SRT applied (because $MX_{E,OHOv}$ contributes to the VSS).

5. Process volume (based on TSS)

$$\begin{aligned}
 X_{\text{TSS}} &= 4 \text{ kgTSS} / \text{m}^3 \\
 V_R &= MX_{\text{TSS}} / X_{\text{TSS}} \\
 &= 72,053 / 4 \\
 V_R &= 18,010 \text{ m}^3
 \end{aligned}
 \tag{4.20}$$

Due to the longer SRT, a larger tank volume is needed.

6. Nutrient requirements

6.1 Nitrogen requirements for biomass synthesis

$$\begin{aligned}
 N_s &= f_n \cdot MX_{\text{VSS}} / (Q_i \cdot \text{SRT}) \\
 &= (0.10 \cdot 57,405) / (15 \cdot 25) \\
 N_s &= 15.3 \text{ gN/m}^3
 \end{aligned}
 \tag{5.25}$$

6.2 Phosphorus requirements for biomass synthesis

$$\begin{aligned}
 P_s &= f_p \cdot MX_{\text{VSS}} / (Q_i \cdot \text{SRT}) \\
 &= (0.03 \cdot 57,405) / (15 \cdot 25) \\
 P_s &= 4.6 \text{ gP/m}^3
 \end{aligned}
 \tag{5.31}$$

Less nutrients are required as the SRT increases to 25 d.

7. Effluent quality

7.1 COD_e

$$\begin{aligned}
 \text{COD}_e &= S_{\text{U,i}} + f_{\text{cv}} \cdot f_{\text{VT}} \cdot X_{\text{TSS,e}} \quad (\text{non-filtered}) \\
 &= 75 + (1.48 \cdot 0.80 \cdot 15) \\
 &= 96 \text{ gCOD/m}^3
 \end{aligned}$$

7.2 Effluent nitrogen concentrations

Since the SRT has been extended, the system may be able to nitrify. This can be evaluated by calculating the minimum required SRT for nitrification (SRT_{MIN}) against the SRT of 25 d.

$$\text{SRT}_{\text{min}} = 1 / [(\mu_{\text{ANOmax,T}} / S_f) - b_{\text{ANO,T}}] \tag{5.16}$$

If:

$$\begin{aligned}
 \mu_{\text{ANOmax,20}} &= 0.45 \text{ 1/d} \\
 \theta_{\text{NIT}} &= 1.123 \\
 \mu_{\text{ANOmax,T}} &= \mu_{\text{ANOmax,20}} \cdot \theta_{\text{NIT}}^{(14-20)} \\
 &= 0.45 \cdot 1.123^{(14-20)} \\
 \mu_{\text{ANOmax,T}} &= 0.22 \text{ 1/d} \\
 b_{\text{ANO,20}} &= 0.04 \text{ 1/d} \\
 \theta_{b,\text{ANO}} &= 1.029 \\
 b_{\text{ANO,T}} &= b_{\text{ANO,20}} \cdot \theta_{b,\text{ANO}}^{(T-20)} \\
 &= 0.04 \cdot 1.029^{(14-20)} \\
 b_{\text{ANO,T}} &= 0.034 \text{ 1/d}
 \end{aligned}$$

And,

$$\begin{aligned}
 S_f &= 1.25 \quad (\text{suggested}) \\
 \text{SRT}_{\text{min}} &= 1 / [(0.224 / 1.25) - 0.034] \\
 &= 6.6 \text{ d}
 \end{aligned}$$

The applied SRT of 25 days is longer than SRT_{MIN} . Thus, nitrification will take place and the TKN_e will need to be calculated as:

$$TKN_e = SN_{Hx,e} + N_{ous,i}$$

And, since the system can nitrify, the expected concentration of nitrate in the effluent can be calculated as:

$$SNO_{3,e} = NIT_c = N_i - N_s - TKN_e$$

Overall, because the system can nitrify, the influence of the nitrification process needs to be added and taken into account in the design even though the system was initially designed for only carbon removal. For that purpose, the influent nitrogen fractions also need to be known. This is covered in Chapter 5 of this book (Example 5.3.1).

In any case (assuming that there is no nitrate present in the influent), the expected effluent total nitrogen concentration (composed of TKN_e , $SNO_{3,e}$ and organic nitrogen) can be computed as:

$$\begin{aligned} N_e &= TKN_e + SNO_{3,e} + f_n \cdot f_{VT} \cdot X_{TSS,e} = TKN_i - N_s + f_n \cdot f_{VT} \cdot X_{TSS,e} \\ &= TKN_i - N_s + f_n \cdot f_{VT} \cdot X_{TSS,e} \\ &= 44.5 - 15.3 + (0.10 \cdot 0.80 \cdot 15) \end{aligned}$$

$$N_e = 30.4 \text{ gN/m}^3$$

7.3. P_e

$$\begin{aligned} P_e &= P_i - P_s + f_p \cdot f_{VT} \cdot X_{TSS,e} \quad (\text{non-filtered}) \\ &= 14.5 - 4.6 + (0.03 \cdot 0.80 \cdot 15) \\ &= 10.3 \text{ gP/m}^3 \end{aligned}$$

Overall, the system is still able to comply with the effluent total COD discharge limit of 125 mgCOD/l. It also produces a treated effluent that contains a total nitrogen and total phosphorus concentration of 30.4 mgN/l and 10.3 mgP/l, respectively.

This indicates that although the system is not designed for nutrient removal, it is able to remove approximately 34 % and 32 % of the nitrogen and phosphorus concentrations present in the influent wastewater, respectively. It is important to underline that these effluent concentrations have been estimated considering that the effluent TSS is 15 mgTSS/l. If the effluent TSS is different, then other concentrations can be expected.

8. Oxygen demand (OD)

OD for synthesis and endogenous respiration

$$FO_{OHO} = FO_{OHO,s} + FO_{OHO,e} \quad (6.30a)$$

$$\begin{aligned} FO_{OHO,s} &= FCOD_{b,OHO} \cdot (1 - f_{cv} \cdot Y_{OHOv}) \\ &= 5,460 \cdot (1 - 1.48 \cdot 0.45) \end{aligned}$$

$$FO_{OHO,s} = 1,824 \text{ kgO}_2/\text{d}$$

$$\begin{aligned} FO_{OHO,e} &= FCOD_{b,OHO} \cdot f_{cv} \cdot (1 - f_{XE,OHO}) \cdot b_{OHO,T} \cdot Y_{OHOv,obs} \cdot SRT \\ &= 5,460 \cdot 1.48 \cdot (1 - 0.20) \cdot 0.202 \cdot 0.074 \cdot 25 \end{aligned}$$

$$FO_{OHO,e} = 2,429$$

$$FO_{OHO} = 4,252 \text{ kgO}_2/\text{d}$$

Although the system was originally designed to only perform the COD removal process, the extended SRT can allow the growth of autotrophic nitrifying organisms (ANO) (see Chapter 5 in the text book). However, while their mass ($MX_{ANO,v}$) can be neglected because they have a low growth yield and the influent TKN concentration is lower than the influent COD, ANOs' oxygen consumption can be extremely high and therefore it needs to be estimated as they will increase the oxygen consumption of the plant. The oxygen consumption of ANO can be calculated as:

$$FO_{NIT} = 4.57 \cdot NIT_c \cdot Q_i \quad (\text{based on 5.35, 5.42b and 5.43b})$$

To estimate FO_{NIT} , the influent nitrogen fractions need to be known. This is covered in Chapter 5 in this book (Example 5.3.1). Yet, for the purpose of this example, assuming that all TKN_i can be nitrified (which means that $TKN_e = S_{NH_{X,e}} + N_{ous,i} = 0$, which is not correct since $S_{NH_{X,e}}$ cannot be zero and usually $N_{ous,i}$ is present in the influent wastewater), a rough estimation of the maximum oxygen consumed by the nitrification process would be:

$$\begin{aligned}
 NIT_c &= TKN_i - N_s - TKN_e \\
 &= 44.5 - 15.3 - 0 \\
 NIT_c &= 29.2 \text{ gN/m}^3 \\
 FO_{NIT} &= 4.57 \cdot 15,000 \cdot 0.0292 \\
 FO_{NIT} &= 2,002 \text{ kgO}_2/\text{d}
 \end{aligned}$$

The FO_{NIT} of 2,002 kgO_2/d is a rough estimation of the maximum additional oxygen consumption that the system will have when increasing the SRT to 25 d.

9. Waste of activated sludge

$$\begin{aligned}
 Q_W &= V_R / \text{SRT} \\
 &= 18,010 / 25
 \end{aligned} \tag{4.1}$$

$$Q_W = 720 \text{ m}^3/\text{d}$$

10. COD mass balance verification

Input

$FCOD_i$	8,775	kgCOD/d	100 % IN
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Output

O₂ demand for synthesis and endogenous respiration

FO_c	4,252	kgCOD/d	48.5 %
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Soluble unbiodegradable organics leaving via the effluent

$FS_{U,i}$	1,125	kgCOD/d	12.8 %
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<i>Sludge</i>	<i>gVSS</i>	<i>gCOD/d</i>	
$(= gVSS \cdot f_{cv} / \text{SRT} = gVSS \cdot 1.48 / 25 = gVSS \cdot 0.0592)$			

$MX_{OHO_v}(=MX_B)$	10,156	601	kgCOD/d	6.8 %
MX_{E,OHO_v}	10,256	607	kgCOD/d	6.9 %
MX_{U_v}	36,993	2,190	kgCOD/d	25.0 %
$MX_{E,OHO} + MX_{U_v}$	47,249	2,797		31.9 %
MX_{VSS}	57,405	3,398	kgCOD/d	38.7 %
Sum:		8,775	kgCOD/d	100 % OUT
Delta (OUT-IN):	0		kgCOD/d	0 %

The 100 % mass balance for COD indicates that all the influent COD is accounted for in the calculated values of oxygen demand and sludge production. From the COD mass balance, and for the conditions of the design example, the fate of the influent COD is as follows: 48.5 % is oxidized with oxygen, 12.8 % escapes in the effluent as soluble unbiodegradable organics and 38.7 % becomes activated sludge. This activated sludge is composed of 17.7 % (10,156 / 57,405) active biomass and 82.3 % (47,249 / 57,405) inactive particulate matter. This indicates that the activated sludge waste can be considered stabilized or inactive as a consequence

of having increased the SRT to 25 d. A summary of the process design results and a comparison with the design in Example 4.3.1 is presented in Table 4.7.

Table 4.7 Summary and comparison between the design carried out with SRT of 6 and 25 days.

Description	Parameter	Unit	SRT 6 d	SRT 25 d
1. Influent and bioreactor				
Type of wastewater	raw		raw	raw
Temperature	T	°C	14	14
Influent flow rate	Q_i	MLD	15	15
Influent total COD	COD_i	gCOD/m ³	585	585
Influent biodegradable COD	$COD_{b,i}$	gCOD/m ³	364	364
Influent TKN	TKN_i	gN/m ³	44.5	44.5
Influent total P	P_i	gP/m ³	14.5	14.5
Sludge recycle ratio (s)	s	m ³ .d / m ³ .d	0.67	0.67
2. $COD_{b,i}$ for OHOs				
Flux of $COD_{b,i}$ for OHOs	$FCOD_{b,OH0}$	kgCOD/d	5,460	5,460
3. System biomass (VSS) equations				
Mass of OHOs	MX_{OH0v}	kgVSS	6,661	10,156
Mass of endogenous residue from OHOs	$MX_{E,OH0v}$	kgVSS	1,616	10,256
Mass of unbiodegradable organics from influent	MX_{Uv}	kgVSS	8,878	36,993
4. Volatile and total suspended solids (VSS and TSS) in system				
Mass of active biomass (= MX_{OH0v})	MX_B	kgVSS	6,661	10,156
Mass of VSS	MX_{VSS}	kgVSS	17,156	57,405
MX_B/VSS	f_{av}	gVSS/gVSS	0.39	0.18
Mass of fixed or inorganic SS	MX_{FSS}	kgFSS	4,149	14,647
Mass of TSS	MX_{TSS}	kgTSS	21,305	72,053
Ratio of VSS/TSS	f_{VT}	gVSS/gTSS	0.81	0.80
5. Reactor volume				
Bioreactor volume	V_R	m ³	5,326	18,010
6. Waste of activated sludge				
Activated sludge waste flow rate	Q_w	m ³ /d	888	720
7. Nutrient requirement				
N requirement concentration for biomass synthesis	N_s	gN/m ³	19.1	15.3
P requirement concentration for biomass synthesis	P_s	gP/m ³	5.7	4.6
8. Oxygen demand				
Flux of carbonaceous O ₂ demand	FO_c	kgO ₂ /d	3,418	4,252 (+2,002) ^{a)}
9. Treated effluent quality^{a)}				
Effluent total COD	COD_e	gCOD/m ³	93	93

Effluent total nitrogen	N_e	gN/m^3	26.6	30.4
Effluent total Kjeldahl Nitrogen	TKN_e	gN/m^3	26.6	$\ll 26.6^{\text{a})}$ $(\text{SNH}_{\text{x,e}} + \text{N}_{\text{ous,i}})$
Effluent nitrate concentration	$\text{SNO}_{3,\text{e}}$	gN/m^3	0	
Effluent total phosphorus	P_e	gP/m^3	9.2	10.3

10. COD mass balance

COD output/COD input	COD mass balance	gCOD/gCOD	100 %	100 %
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Flow rate is in m^3/d and mass fluxes in kg/d .

For a flow rate of 1,000 or greater, mass fluxes can be read in kg/d .

^{a)} Since the SRT of 25 days $>$ SRT_{min} (6.6 days), the system will nitrify and the contribution of the ANO to the oxygen consumption and effluent nitrogen concentrations need to be calculated.

When the system is increased from 6 days to 25 days SRT, the system generates approximately 19 % less sludge waste (888 versus 720 m^3/d , correspondingly) that, based on the active biomass ratio (f_{av}), is also less active (0.39 compared to 0.18). At the SRT of 25 days, the generation of less stabilized sludge waste makes it easier to handle and it could possibly be merely dehydrated prior to disposal (whereas at the SRT of 6 days the sludge needs to be digested 'to make it stable'). However, the longer SRT has implications on (i) the tank volume (that increased more than 3 times), (ii) oxygen requirements (by at least 25 % but that could double if the oxygen requirements due to nitrification are included) and (iii) the effluent quality (where the nutrient concentrations increased slightly at the SRT of 25 days, a high concentration of nitrate can be expected). These advantages and disadvantages need to be carefully taken into account when deciding to design an activated sludge plant with short or long SRT (e.g., 6 and 25 d, as in this example).

Example 4.3.4

The plant from Example 4.3.1 was designed with an average total solids concentration in the reactor (X_{TSS}) of 4 kgTSS/m^3 , resulting in a reactor tank volume (V_R) of 5,326 m^3 to treat the influent wastewater flow rate of 15 MLD (15,000 m^3/d) that has a peak factor (f_q) of 3.5. However, a secondary settling tank has not been designed. Furthermore, the unit price to construct the aeration tanks are (as a function of the volume range):

Volume range (m^3)	Unit price ^{a)} ($\text{€}/\text{m}^3$)
$< 1,250$	360
1,251-2,500	270
2,501-5,000	220
5,001-10,000	180
10,001-25,000	160

^{a)} Unit prices are estimated in The Netherlands in the year 2020 for prefabricated concrete elements.

To design the settling tanks, a circular configuration will be considered, taking into account 2 main treatment lines (N_{AS}), each one with 2 secondary settling tanks (N_{SST}). For this purpose, the following settling properties of the sludge are assumed: a maximum settling velocity (v_o) of 8.6 m/h and a hindrance coefficient (r_{hin}) of 0.486 m^3/kg . Thus, the area of the secondary settling tank can be found as follows:

$$A_{\text{SST}} = 1,000 \cdot f_q \cdot (Q_{i, \text{ADWF}} / 24) / [0.80 \cdot v_o \cdot \exp(-r_{\text{hin}} \cdot X_{\text{TSS}}) \cdot N_{\text{AS}} \cdot N_{\text{SST}}] \quad (4.31)$$

The estimated costs of the circular settling tanks, as a function of their diameter, are as follows:

Diameter (m)	Unit price ^{b)} (€/m ²)
< 20	790
21-25	710
26-30	650
31-35	610
36-40	580
41-50	560
> 50	540

^{b)} Estimated unit price in The Netherlands in the year 2020 for prefabricated concrete elements.

The main question is: what would be the optimal X_{TSS} concentration that could minimize the construction costs to build these two treatment units?

Solution

Using the data provided, Table 4.8 shows the detailed calculations to determine the X_{TSS} that would lead to the lowest construction costs of the aerobic reactor and the secondary settling tank.

Table 4.8 Determination of the optimal X_{TSS} concentration to minimize the construction costs of the aerobic reactor and secondary settling tank

1. Aerobic reactor volume costs			
V_R	$= MX_{TSS} / X_{TSS}$		
	$= 21,305 / X_{TSS}$		
(4.20)			
For different X_{TSS} :			
X_{TSS} (kgTSS/m ³)	V_R (m ³)	Unit price (€/m ³)	Cost (€)
1.0	21,305	160	3,408,800
1.5	14,203	160	2,272,533
2.0	10,653	160	1,704,400
2.5	8,522	180	1,533,960
3.0	7,102	180	1,278,300
3.5	6,087	180	1,095,686
4.0	5,326	180	958,725
4.5	4,734	220	1,041,578
5.0	4,261	220	937,420
2. Secondary settling tank costs			
A_{SST}	$= 1,000 \cdot f_q \cdot (Q_{i,ADWF} / 24) / [0.80 \cdot v_o \exp(-r_{hin} \cdot X_{TSS}) \cdot N_{AS} \cdot N_{SST}]$		
(4.31)			
Where:			
f_q	3.5		
$Q_{i,ADWF}$	15	MLD	
v_o	8.6	m/h	
r_{hin}	0.486	m ³ /kg	
N_{AS}	2	No. main treatment lines	
N_{SST}	2	No. settling tanks per treatment line	

Thus:

$$A_{SST} = 1,000 \cdot (3.5 \cdot 15 / 24) / [(0.80 \cdot 8.6 \exp(-0.486 \cdot X_{TSS}) \cdot 2 \cdot 2)]$$

As a function of X_{TSS} :

X_{TSS} (kgTSS/m ³)	A_{SST} (m ²) (of 1 tank)	Diameter (m)	Unit price (€/m ²)	Cost (€) (for 1 tank)	Costs of all tanks (€)
1.0	129	13	790	102,093	408,370
1.5	165	14	790	130,175	520,700
2.0	210	16	790	165,982	663,928
2.5	268	18	790	211,638	846,554
3.0	342	21	710	242,527	970,106
3.5	436	24	710	309,238	1,236,952
4.0	555	27	650	360,979	1,443,914
4.5	708	30	650	460,272	1,841,090
5.0	903	34	610	550,763	2,203,054

3. Total construction costs of the aerobic reactors and secondary settling tanks

X_{TSS} (kgTSS/m ³)	Aeration tank cost (€)	Settling tank costs (€)	Total costs (€)
1.0	3,408,800	408,370	3,817,170
1.5	2,272,533	520,700	2,793,233
2.0	1,704,400	663,928	2,368,328
2.5	1,533,960	846,554	2,380,514
3.0	1,278,300	970,106	2,248,406
3.5	1,095,686	1,236,952	2,332,638
4.0	958,725	1,443,914	2,402,639
4.5	1,041,578	1,841,090	2,882,668
5.0	937,420	2,203,054	3,140,474

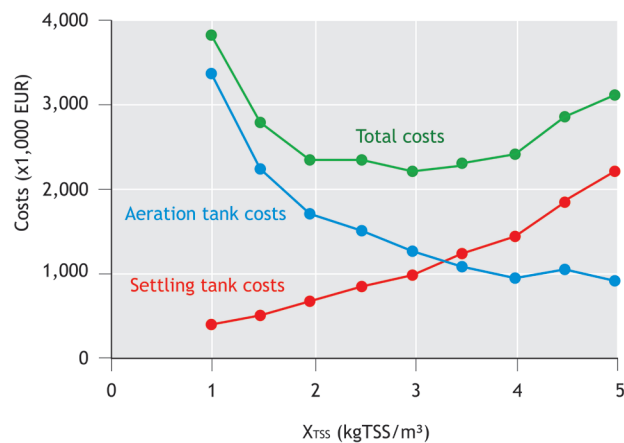


Figure 4-3 Construction costs of the activated sludge plant: aeration tank costs, settling tank costs, and total costs.

As observed in Table 4.8 and Figure 4.3 (Total costs line), the lowest cost is obtained with the X_{TSS} of 3.0 kgTSS/m³, followed by the costs obtained at the concentrations of 3.5, 2.0, 2.5 and 4.0 kg TSS/m³. This indicates that although the X_{TSS} of 4 kgTSS/m³ leads to one of the most economical options, it is not the most economical. While the higher X_{TSS} concentration decreases the volume of the aerobic reactor, it tends to increase A_{SST} because the settling tanks are more loaded which increases the construction costs of the plant.

4.4 EXERCISES

Exercise 4.4.1

Explain the fate of the biodegradable soluble and particulate organics in a CAS system.

Exercise 4.4.2

Explain the fate of the unbiodegradable soluble and particulate organics in a CAS system.

Exercise 4.4.3

Explain what the sources of inorganic or fixed suspended solids and the fate of the unbiodegradable soluble and particulate organics are in a conventional activated sludge system.

Exercise 4.4.4

Explain why a certain percentage of the influent nutrient concentrations are removed in a fully aerobic activated sludge plant even if it is not designed for the removal of nutrients.

Exercise 4.4.5

Given the following wastewater characteristics and COD fractionation, determine the minimum total COD and soluble COD that would be present in the effluent, assuming that the CAS and its secondary settling tank operate under ideal conditions.

COD fraction	COD (mg/l)	COD fraction	COD (mg/l)
$S_{s,i}$	153	$S_{u,i}$	32
$X_{s,i}$	67	$X_{u,i}$	74

Exercise 4.4.6

For the previous COD fractionation, what would be the COD fluxes flowing into the aerobic reactor if the influent flow rate Q_i is 12.5 MLD?

Exercise 4.4.7

Given the following wastewater characteristics and COD fractionation, and considering an effluent solids concentration of 32 mg TSS/l with a f_{VT} ratio of 0.85, will the COD_e be able to meet a standard COD_e of 125 mgCOD/l?

COD fraction	COD (mg/l)	COD fraction	COD (mg/l)
$S_{s,i}$	174	$S_{u,i}$	123
$X_{s,i}$	215	$X_{u,i}$	156

Exercise 4.4.8

For the COD fractionation from Exercise 4.4.7, an influent flow rate (Q_i) of 25 MLD and assuming that a primary settling tank (PST) is installed before the aerobic reactor and operates under ideal conditions, what would be the COD fluxes flowing into the aerobic reactor?

Exercise 4.4.9

For the following COD fractionation ($COD_i = 624 \text{ gCOD/m}^3$), a CAS has been designed to treat an influent flow rate (Q_i) of 25 MLD with an SRT of 10 d to operate at a temperature of 18°C . The proposed s-recycle ratio is 0.75 and an average X_{TSS} in the aerobic reactor of 4 kgTSS/m^3 . The influent contains 21 mgFSS/l and the expected $X_{TSS,e}$ is 20 mg/l . If the plant operators decide to minimize costs, what SRT can you suggest and what would be the potential savings?

COD fraction	COD (mg/l)	COD fraction	COD (mg/l)
$S_{s,i}$	187	$S_{u,i}$	96
$X_{s,i}$	205	$X_{u,i}$	136

Exercise 4.4.10

If the plant from Exercise 4.4.9 was designed with SRT of 4 days and with a primary settling tank (PST) that removes 0.5% of Q_i as settled sludge, what will be the implications for the design?

Exercise 4.4.11

For the plant in Exercise 4.4.9, what design considerations need to be made to achieve a stable WAS that does not require a sophisticated sludge handling line?

Exercise 4.4.12

If the plant from Exercise 4.4.11 was designed with SRT of 22 days and an average total solids concentration in the reactor (X_{TSS}) of 4 kgTSS/m^3 , a reactor tank volume (V_R) of $24,231 \text{ m}^3$ will be needed to treat the influent wastewater of 25 MLD ($25,000 \text{ m}^3/\text{d}$) that has a peak factor (f_q) of 4.0. However, a secondary settling tank (SST) has not been designed. Furthermore, the unit price to construct the aeration tanks are (as a function of the volume range):

Volume range (m^3)	Unit price ^{a)} ($\text{€}/\text{m}^3$)
< 1,250	360
1,251-2,500	270
2,501-5,000	220
5,001-10,000	180
10,001-25,000	160

^{a)} Estimated unit price in The Netherlands in the year 2020 for prefabricated concrete elements.

To design the aeration tanks, assume that 3 mainstream treatment lines (N_{AS}) and 2 secondary settling tanks per treatment line (N_{SST}) are constructed. For the secondary settling tanks, consider a circular configuration and the following design parameters: a maximum settling velocity (v_o) of 8.1 m/h and a hindrance coefficient (r_{hin}) of $0.395 \text{ m}^3/\text{kg}$.

The estimated costs of the circular settling tanks, as a function of their diameter, are the following:

Diameter (m)	Unit price ^{b)} (€/m ²)
< 20	790
21-25	710
26-30	650
31-35	610
36-40	580
41-50	560
> 50	540

^{b)} Estimated unit price in The Netherlands in the year 2020 for prefabricated concrete elements.

What would be the optimal X_{TSS} concentration that could minimize the construction costs of the activated sludge system?

Exercise 4.4.13

Let us assume that the plant designed in Example 4.3.1 with the SRT of 6 days was finally built with 2 mainstream treatment lines. Each treatment line has 1 aerobic tank reactor of 2,663 m³ at an average X_{TSS} of 4 kgTSS/m³ and 2 secondary settling tanks with a diameter of 27 m. In total, the total volume of the aeration tanks is 5,326 m³ (of the two aerobic tanks) and a total settling area of 2,290 m² (of the four final settlers, Example 4.3.4, Table 4.8). However, in the coming year, the plant will receive a discharge of 1.5 MLD of an additional highly biodegradable industrial effluent from a food and processing industry with a COD_i of 1,378 mgCOD/l. The industrial effluent does not contain any toxic compounds and its COD fractionation is:

COD fraction	COD (mg/l)	COD fraction	COD (mg/l)
$S_{s,i}$	1,253	$S_{u,i}$	60
$X_{s,i}$	50	$X_{u,i}$	305

The designers of the plant would like to know if the activated sludge plant is robust enough to treat the additional COD load.

ANNEX 1: SOLUTIONS TO EXERCISES

Solution 4.4.1

Both the biodegradable soluble and the biodegradable particulate organics will be mostly converted into new biomass cells. The difference is that the biodegradable soluble organics are rapidly converted whereas the biodegradable particulate organics get enmeshed in the sludge flocs, being slowly hydrolysed prior to their conversion into new biomass.

Solution 4.4.2

Soluble unbiodegradable organics cannot be removed either biologically (e.g., for the synthesis of new cell biomass) or physically (e.g., because they are soluble and do not get enmeshed in the sludge flocs). Thus, soluble unbiodegradable organics leave through the effluent of the activated sludge plant. Unbiodegradable particulate organics cannot be removed biologically but are enmeshed in the sludge flocs, accumulating in the system and ultimately being removed via the waste of activated sludge.

Solution 4.4.3

Inorganic suspended solids can be present in the influent wastewater depending on the origin and quality of the wastewater (e.g., if hard water is supplied to the water network or if saline water intrusion or groundwater infiltration occurs). In addition, active biomass cells need inorganic compounds (e.g., micronutrients) to carry out their microbial metabolism and therefore they accumulate in the activated sludge plant as a function of the active biomass.

Solution 4.4.4

Ordinary heterotrophic organisms, the dominant organisms in activated sludge systems, require (macro-) nutrients, mostly nitrogen and phosphorus, to synthesize new biomass cells. They cover these biomass nutrient requirements by consuming the nutrients present in the influent wastewater.

Solution 4.4.5

If the CAS and its secondary settling tank operate under ideal conditions: total COD = COD_e = S_{U,i} = 32 mg/l. Otherwise, the minimum soluble COD = S_{U,i} = 32 mg/l and total COD = COD_e = S_{U,i} + f_{cv} · X_{VSS,e} where X_{VSS,e} will depend on the efficiency of the secondary settling tank.

Solution 4.4.6

$$\text{FCOD}_i = 4,075 \text{ kgCOD/d}$$

$$\text{FCOD}_{b,i} = 2,750 \text{ kgCOD/d}$$

$$\text{FX}_{U,i} = 925 \text{ kgCOD/d}$$

$$\text{FX}_{U,v,i} = 625 \text{ kgVSS/d}$$

Solution 4.4.7

Total COD = COD_e = S_{U,i} + f_{cv} · f_{VT} · X_{TSS,e} = 123 + (1.48 · 0.85 · 32) = 163.3 mg COD/l. Therefore, the discharge standard of 125 mg COD/l cannot be met.

Solution 4.4.8

Ideally, both particulate organics (biodegradable and unbiodegradable) will be settled out in the PST. Therefore:

$$\text{FCOD}_i = 7,425 \text{ kgCOD/d}$$

$$\text{FCOD}_{b,i} = 4,350 \text{ kgCOD/d}$$

Solution 4.4.9

Due to the temperature of 18 °C, the system could be designed with SRT of 4 days (instead of the SRT of 10 days to minimize the construction and operational costs of the plant):

Table 4.9 Summary and comparison between the design carried out with an initial SRT of 10 days and SRT of 4 days.

Description	Parameter	Unit	SRT 10 d	SRT 4 d
1. Influent and bioreactor				
Type of wastewater	raw		raw	raw
Temperature	T	°C	18	18
Influent flow rate	Q_i	MLD	25	25
Influent total COD	COD_i	gCOD/m ³	624	624
Influent biodegradable COD	$COD_{b,i}$	gCOD/m ³	392	392
Sludge recycle ratio (s)	s	m ³ .d / m ³ .d	0.75	0.75
2. $COD_{b,i}$ for OHOs				
Flux of $COD_{b,i}$ for OHOs	$FCOD_{b,OH0}$	kgCOD/d	9,800	9,800
3. System biomass (VSS) equations				
Mass of OHOs	MX_{OH0v}	kgVSS	13,514	9,261
Mass of endogenous residue from OHOs	$MX_{E,OH0v}$	kgVSS	6,126	1,679
Mass of unbiodegradable organics from influent	MX_{Uv}	kgVSS	22,973	9,189
4. Volatile and total suspended solids (VSS and TSS) in system				
Mass of active biomass (= MX_{OH0v})	MX_B	kgVSS	13,514	9,261
Mass of VSS	MX_{VSS}	kgVSS	42,613	20,130
MX_B/VSS	f_{av}	gVSS/gVSS	0.32	0.46
Mass of fixed or inorganic SS	MX_{FSS}	kgFSS	7,277	3,489
Mass of TSS	MX_{TSS}	kgTSS	49,890	23,619
Ratio of VSS/TSS	f_{VT}	gVSS/gTSS	0.85	0.85
5. Reactor volume				
Bioreactor volume	V_R	m ³	12,472	5,905
6. Waste of activated sludge				
Activated sludge waste flow rate	Q_W	m ³ /d	1,247	1,476
7. Nutrient requirement				
N concentration needed for biomass synthesis	N_s	gN/m ³	17.0	20.1
P concentration needed for biomass synthesis	P_s	gP/m ³	5.1	6.0
8. Oxygen demand ^{a)}				
Flux of carbonaceous O ₂ demand	FO_C	kgO ₂ /d	6,893	5,752
9. Treated effluent quality				
Effluent total COD	COD_e	gCOD/m ³	121	121
10. COD mass balance				
COD output/COD input	COD mass balance	gCOD/gCOD	100 %	100 %

^{a)} Due to the temperature (18°C), the system will probably be able to nitrify at SRT of 10 days and maybe even at SRT of 4 days. This needs to be verified since it could affect the oxygen requirements of the plant.

By shortening the SRT from 10 to 4 days, considerable savings can be expected in reactor tank volumes (to less than half the original required volume) and oxygen requirements (17%). However, the activated sludge waste will increase (by 18%) and this implies that the sludge handling line may need to be expanded.

Solution 4.4.10

If a PST is installed, ideally both particulate organics will be settled out. Thus, the design will be as follows:

Table 4.10 Summary of the design carried out with the SRT of 4 days and after installing a PST.

Description	Parameter	Unit	SRT 4 d	SRT 4 d with PST
1. Influent and bioreactor				
Type of wastewater	raw		raw	settled
Temperature	T	°C	18	18
Influent flow rate	Q_i	MLD	25	24.875
Influent total COD	COD_i	gCOD/m ³	624	283
Influent biodegradable COD	$COD_{b,i}$	gCOD/m ³	392	187
Sludge recycle ratio (s)	s	m ³ .d / m ³ .d	0.75	0.75
2. $COD_{b,i}$ for OHOs				
Flux of $COD_{b,i}$ for OHOs	$FCOD_{b,OHO}$	kgCOD/d	9,800	4,652
3. System biomass (VSS) equations				
Mass of OHOs	MX_{OHOv}	kgVSS	9,261	4,396
Mass of endogenous residue from OHOs	$MX_{E,OHOv}$	kgVSS	1,679	797
Mass of unbiodegradable organics from influent	MX_{Uv}	kgVSS	9,189	0
4. Volatile and total suspended solids (VSS and TSS) in system				
Mass of active biomass (= MX_{OHOv})	MX_B	kgVSS	9,261	4,396
Mass of VSS	MX_{VSS}	kgVSS	20,130	5,193
MX_B/VSS	f_{av}	gVSS/gVSS	0.46	0.85
Mass of fixed or inorganic SS	MX_{FSS}	kgFSS	3,489	659 ^{b)}
Mass of TSS	MX_{TSS}	kgTSS	23,619	5,852
Ratio of VSS/TSS	f_{VT}	gVSS/gTSS	0.85	0.89
5. Reactor volume				
Bioreactor volume	V_R	m ³	5,905	1,463
6. Waste of activated sludge				
Activated sludge waste flow rate	Q_W	m ³ /d	1,476	366
7. Nutrient requirement				
N requirement concentration for biomass synthesis	N_s	gN/m ³	20.1	5.2
P requirement concentration for biomass synthesis	P_s	gP/m ³	6.0	1.6
8. Oxygen demand^{a)}				
Flux of carbonaceous O ₂ demand	FO_C	kgO ₂ /d	5,752	2,730

9. Treated effluent quality

Effluent total COD	COD _e	gCOD/m ³	121	122
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10. COD mass balance

COD output/COD input	COD mass balance	gCOD/gCOD	100 %	100 %
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^{a)} Due to the temperature (18°C), the system will probably be able to nitrify at SRT of 10 days and maybe even at SRT of 4 days. This needs to be verified since it could affect the oxygen requirements of the plant.

^{b)} Also, due to the PST the concentration of influent ISS may be removed decreasing the MX_{FSS}.

By introducing the PST, considerable savings can be expected in reactor tank volumes (to approximately 25 % of the volume required without PST) and oxygen requirements (to almost 47 %). However, the main implication in the design will be the need to treat the sludge settled out in the PST. Assuming that the underflow rate is of approximately 0.5 % Q_i, the COD flux to be treated in the sludge handling line will be around 8,560 kgCOD/d. This flux and its volume (of 125 m³/d) needs to be considered to design the sludge treatment line in addition to the Q_w.

Solution 4.4.11

To produce a stabilized digested WAS, the minimum applied SRT should be 22 days.

Table 4.11 Summary of the design carried out with the SRT of 22 days and comparison against the designs performed at SRT of 4 and 10 days.

Description	Parameter	Unit	SRT 4 d	SRT 10 d	SRT 22 d
1. Influent and bioreactor					
Type of wastewater	raw		raw	raw	raw
Temperature	T	°C	18	18	18
Influent flow rate	Q _i	MLD	25	25	25
Influent total COD	COD _i	gCOD/m ³	624	624	624
Influent biodegradable COD	COD _{b,i}	gCOD/m ³	392	392	392
Sludge recycle ratio (s)	s	m ³ .d / m ³ .d	0.75	0.75	0.75
2. COD_{b,i} for OHOs					
Flux of COD _{b,i} for OHOs	FCOD _{b,OHo}	kgCOD/d	9,800	9,800	9,800
3. System biomass (VSS) equations					
Mass of OHOs	MX _{OHov}	kgVSS	9,261	13,514	16,222
Mass of endogenous residue from OHOs	MX _{E,OHov}	kgVSS	1,679	6,126	16,179
Mass of unbiodegradable organics from influent	MX _{Uv}	kgVSS	9,189	22,973	50,541
4. Volatile and total suspended solids (VSS and TSS) in system					
Mass of active biomass (=MX _{OHov})	MX _B	kgVSS	9,261	13,514	16,222
Mass of VSS	MX _{VSS}	kgVSS	20,130	42,613	82,942
MX _B /VSS	f _{av}	gVSS/gVSS	0.46	0.32	0.20
Mass of fixed or inorganic SS	MX _{FSS}	kgFSS	3,489	7,277	13,983
Mass of TSS	MX _{TSS}	kgTSS	23,619	49,890	96,925
Ratio of VSS/TSS	f _{VT}	gVSS/gTSS	0.85	0.85	0.86

5. Reactor volume					
Bioreactor volume	V_R	m^3	5,905	12,472	24,231
6. Waste of activated sludge					
Activated sludge waste flow rate	Q_W	m^3/d	1,476	1,247	1,101
7. Nutrient requirement					
N requirement concentration for biomass synthesis	N_s	gN/m^3	20.1	17.0	15.1
P requirement concentration for biomass synthesis	P_s	gP/m^3	6.0	5.1	4.5
8. Oxygen demand ^{a)}					
Flux of carbonaceous O_2 demand	FOC	kgO_2/d	5,752	6,893	7,620
9. Treated effluent quality					
Effluent total COD	COD_e	$gCOD/m^3$	121	121	121
10. COD mass balance					
COD output/COD input	COD mass balance	$gCOD/gCOD$	100 %	100 %	100 %

^{a)} Due to the temperature (18°C), the system will be able to nitrify at SRT of 10 days and SRT of 22 days. This needs to be verified since it could affect the oxygen requirements of the plant.

By increasing the SRT to 22d, a stable Q_W of 1,101 m^3/d (up to 25 % lower with regard to the SRT of 4 days) with an active biomass fraction (MX_B / M_{VSS}) of 0.20 can be generated. This daily Q_W could be treated in a relatively easier manner (e.g., using sludge drying beds) compared to the Q_W produced at shorter SRT. However, it should be noticed that the both the tank volumes and oxygen requirements will increase, impacting the capital investment and running costs of the system.

Solution 4.4.12

The lowest cost of approximately €6,315,971 could be obtained with a X_{TSS} of 5.0 $kgTSS/m^3$, followed rather closely by the costs obtained at the concentrations of 4.5 and 4.0 $kg TSS/m^3$ (of €6,349,211 and €6,390,767, respectively). However, these costs refer to capital investment and the X_{TSS} of 5.0 $kgTSS/m^3$ may decrease the oxygen transfer efficiency in the aerobic reactor which could increase the running costs of the plant. Thus, it can be more convenient to design and operate the plant at the X_{TSS} of 4.0 or 4.5 $kgTSS/m^3$, concentrations at which the oxygen transfer will be higher.

Solution 4.4.13

First, the effect of the discharge of the industrial effluent on the existing plant is evaluated. However, since, as explained below, certain parameters are exceeded, the calculations are also done shortening the SRT from 6 to 4.5 days as an alternative operational strategy. A summary of the calculations is displayed in Table 4.12.

Table 4.12 Summary of the design carried out with the SRT of 22 days and comparison against the designs performed at SRT of 4 and 10 days.

Description	Parameter	Unit	SRT 6 d	SRT 6 d	SRT 4.5 d
1. Influent and bioreactor					
Type of wastewater	raw		raw	raw plus industrial	raw plus industrial
Temperature	T	°C	14	14	14
Influent flow rate	Q_i	MLD	15	16.5	16.5
Influent total COD	COD_i	gCOD/m ³	585	684	684
Influent biodegradable COD	$COD_{b,i}$	gCOD/m ³	364	449	449
Sludge recycle ratio (s)	s	m ³ .d / m ³ .d	0.67	0.67	0.67
2. $COD_{b,i}$ for OHOs					
Flux of $COD_{b,i}$ for OHOs	$FCOD_{b,OHO}$	kgCOD/d	5,460	7,415	7,415
3. System biomass (VSS) equations					
Mass of OHOs	MX_{OHOv}	kgVSS	6,661	9,046	7,862
Mass of endogenous residue from OHOs	$MX_{E,OHOv}$	kgVSS	1,616	2,195	1,430
Mass of unbiodegradable organics from influent	MX_{Uv}	kgVSS	8,878	10,733	8,050
4. Volatile and total suspended solids (VSS and TSS) in system					
Mass of active biomass (= MX_{OHOv})	MX_B	kgVSS	6,661	9,046	7,862
Mass of VSS	MX_{VSS}	kgVSS	17,156	21,974	17,342
MX_B/VSS	f_{av}	gVSS/gVSS	0.39	0.41	0.45
Mass of fixed or inorganic SS	MX_{FSS}	kgFSS	4,149	4,507	3,542
Mass of TSS	MX_{TSS}	kgTSS	21,305	26,481	20,884
Ratio of VSS/TSS	f_{VT}	gVSS/gTSS	0.81	0.83	0.83
5. Reactor volume and X_{TSS}					
Bioreactor volume	V_R	m ³	5,326	5,326	5,326
Average total solids concentration	X_{TSS}	g/m ³	4	4.97	3.92
6. Waste of activated sludge					
Activated sludge waste flow rate	Q_W	m ³ /d	888	888	1,160
7. Nutrient requirement					
N requirement concentration for biomass synthesis	N_s	gN/m ³	19.1	22.2	23.4
P requirement concentration for biomass synthesis	P_s	gP/m ³	5.7	6.7	7.0
8. Oxygen demand					
Flux of carbonaceous O ₂ demand	FO_C	kgO ₂ /d	3,418	4,642	4,358
9. Treated effluent quality					
Effluent total COD	COD_e	gCOD/m ³	93	92	92
10. COD mass balance					
COD output/COD input	COD mass balance	gCOD/gCOD	100 %	100 %	100 %

If the plant receives the additional industrial effluent COD load operating at SRT of 6 days, the X_{TSS} would increase to 4.97 kgTSS/m^3 and the FO_c to $4,642 \text{ kgO}_2/\text{d}$. These can be seen as minor increases and the aerobic tank would probably be able to cope with the increased COD load. However, the increased combined Q_i of 16.5 MLD combined with the X_{TSS} of 4.97 kgTSS/m^3 have a major impact on the required area of the secondary settling tanks. The total required settling area would increase from 555 m^2 to 979 m^2 . This is an increase of about 75 % which will take the 4 secondary settling tanks above their capacity. Alternatively, the plant could decrease their SRT to 4.5 d and, since the changes are minimal compared to the operation before the industrial effluent addition (last column from Table 4.12), both the aerobic and the final setting stages could work well. However, the Q_w would increase by 20 % from 888 to $1,160 \text{ m}^3/\text{d}$. This alternative could be feasible if the sludge handling facilities could cope with the increased Q_w . Still, the aeration capacity needs to be expanded to match the increased requirements for oxygen (of $4,358 \text{ kgO}_2/\text{d}$).

REFERENCE

Chen GH., van Loosdrecht M.C.M., Ekama G.A. and Brdjanovic D. Ed. (2020) Biological Wastewater Treatment: Principles, Design and Modelling. 2nd edition. IWA Publishing, pg. 850. 9781789060355.

NOMENCLATURE

Symbol	Description	Units
$(F/M)_{\text{COD,TSS}}$	Food-to-microorganisms ratio calculated based on COD fractionation	kgCOD.d/kgTSS
AND	Total mass to COD ratio for activated sludge systems performing only nitrification and denitrification processes	kgTSS/kgCOD.d
A_{SST}	Area of secondary settling tank	m^2
$b_{\text{ANO},20}$	ANO-specific endogenous mass loss rate constant at 20°C	gVSS/gVSS.d
$b_{\text{ANO},T}$	ANO-specific endogenous mass loss rate constant at temperature T	gVSS/gVSS.d
b_{OHO}	Specific endogenous mass loss rate of the OHOs	gVSS/gVSS.d
$b_{\text{OHO},20}$	Specific endogenous mass loss rate of the OHOs at 20°C	gVSS/gVSS.d
$b_{\text{OHO},T}$	OHO specific endogenous mass loss rate at temperature T	gVSS/gVSS.d
$\text{COD}_{b,i}$	influent concentration of biodegradable COD ($S_{s,i} + X_{s,i}$)	gCOD/m^3
COD_e	Efluent concentration of total COD	gCOD/m^3
COD_i	Concentration of COD in the influent	gCOD/m^3
F/M	Food-to-microorganisms ratio	kgCOD.d/kgTSS
f_{av}	Fraction of active biomass with the regard to the mass of volatile suspended solids	kgVSS/kgVSS
$\text{FCOD}_{b,i}$	Daily mass of influent biodegradable organics ($S_{s,i} + X_{s,i}$)	kgCOD/d
$\text{FCOD}_{b,\text{OHO}}$	Daily mass of biodegradable substrate available to OHOs	kgCOD/d
FCOD_i	Daily mass of influent COD	kgCOD/d
f_{cv}	COD/VSS ratio of the sludge	gCOD/gVSS
$f_{\text{FSS},\text{OHO}}$	Fraction of fixed (inorganic) suspended solids of OHOs	gFSS/gVSS
f_n	Nitrogen content of the sludge	gN/gVSS
FO_c	Daily mass of carbonaceous oxygen demand	kgO_2/d
FO_{NIT}	Daily mass of oxygen consumed by ANO	kgO_2/d
FO_{OHO}	Daily mass of oxygen consumed by OHOs	kgO_2/d

$FO_{OHO,e}$	Daily mass of oxygen consumed by OHOs for endogenous respiration	kgO_2/d
$FO_{OHO,s}$	Daily mass of oxygen consumed by OHOs for synthesis	kgO_2/d
FO_t	Daily mass of total oxygen demand	kgO_2/d
f_P	Fraction of P in the active OHO mass, endogenous mass and unbiodegradable mass	$gP/gVSS$
f_q	Factor for peak wet weather flow	-
$FS_{s,i}$	Influent daily flux of rbCOD	$kgCOD/d$
$fs_{U,CODi}$	Influent unbiodegradable soluble COD fraction	$gCOD/gCOD$
$FS_{U,i}$	Influent daily flux of soluble unbiodegradable COD	$kgCOD/d$
f_{VT}	VSS to TSS ratio of the sludge	$kgVSS/kgTSS$
$FX_{FSS,i}$	Flux of inorganic or fixed suspended solids in the influent	$kgFSS/d$
$fx_{E,OHO}$	Fraction of endogenous residue of the OHOs	$gEVSS/gAVSS$
$FX_{FSS,i}$	Daily mass of influent inorganics	$gFSS/d$
$fx_{U,CODi}$	Influent unbiodegradable particulate COD fraction	$gCOD/gCOD$
$FX_{U,i}$	Influent daily flux of particulate unbiodegradable COD	$kgCOD/d$
$FX_{UV,i}$	Influent daily flux of particulate unbiodegradable organics	$kgVSS/d$
MX_{ANOV}	Mass of ANOs in the system	$gAVSS$
MX_{bio}	Sum of all active biomasses in the system	$gVSS$
$MX_{E,OHOV}$	Mass of OHO endogenous residue in the system	$gEVSS$
MX_{FSS}	Mass of fixed (inorganic) suspended solids in the system	$gFSS$
MX_{OHov}	Mass of OHOs in the system	$gAVSS$
MX_{TSS}	TSS mass in the system	$gTSS$
MX_{Uv}	Mass of unbiodegradable organic matter in the system, coming from the influent	$gVSS$
MX_{VSS}	Mass of volatile suspended solids in the system	$gTSS$
N_{AS}	Number of activated sludge treatment modules in a system	-
N_e	Effluent total nitrogen concentration	gN/m^3
NIT_c	Nitrification capacity of the bioreactor	gNO_3-N/m^3
$N_{ous,i}$	Influent unbiodegradable soluble organic nitrogen	gN/m^3
N_s	Nitrogen required for biomass growth	gN/m^3
N_{SST}	Number of secondary settling tanks per activated sludge treatment modules	-
P_e	Effluent total phosphorus concentration	gP/m^3
P_i	Influent total phosphorus concentration	gP/m^3
P_s	Phosphorus required for biomass growth	gP/m^3
Q_i	Daily average influent flow rate	m^3/d
$Q_{i,ADWF}$	Average dry weather flow	m^3/d
Q_s	Sludge recycle flow rate	m^3/d
r_{hin}	Settling hindrance factor	$m^3/kgTSS$
s	Return activated sludge recycle ratio based on influent flow	$m^3.d/m^3.d$
S_f	Safety factor for the nitrification process	-
$SNH_{x,e}$	Effluent free and saline ammonia	gN/m^3
$SNO_{3,e}$	Effluent nitrate concentration	gNO_3-N/m^3
SRT	Sludge age	d
SRT_{min}	Minimum SRT required for nitrification	d
$SS_{s,i}$	Influent readily biodegradable COD concentration	$gCOD/m^3$
$SU_{s,i}$	Influent concentration of soluble unbiodegradable COD	$gCOD/m^3$

T	Temperature	°C
TKN	Total Kjeldahl nitrogen concentration	gN/m ³
TKN _e	Effluent total Kjeldahl nitrogen	gN/m ³
TKN _i	Influent total Kjeldahl nitrogen concentration	gN/m ³
v _o	Maximum initial settling velocity	m/h
V _R	Volume of biological process (bioreactor)	m ³
X _{FSS,i}	Influent fixed suspended solids (FSS) concentration	gFSS/m ³
X _{TSS,s}	Total suspended-solids concentration in the sludge recycle flowrate	gTSS/m ³
X _S	Slowly biodegradable organics concentration	gCOD/m ³
X _{S,i}	Influent concentration of particulate biodegradable COD	gCOD/m ³
X _{TSS}	Reactor total suspended-solids concentration	gTSS/m ³
X _{TSS,e}	Total suspended-solids concentration in the effluent	gTSS/m ³
X _U	Unbiodegradable particulate COD	gCOD/m ³
X _{U,i}	Influent concentration of unbiodegradable particulate COD	gCOD/m ³
X _{VSS}	Reactor volatile suspended solids concentration	gVSS/m ³
Y _{OHOv}	Biomass yield of OHOs	gVSS/gCOD
Y _{OHOv,obs}	Observed biomass yield of OHOs	gVSS/gCOD
θ _{b,ANO}	Temperature coefficient for b _{ANO,T}	-
θ _{b,OHO}	Temperature coefficient for b _{OHO,T}	-
θ _{NIT}	Temperature coefficient for μ _{ANO,T} and K _{ANO,T}	-
μ _{ANOMax,20}	ANO maximum specific growth rate constant at 20 °C	gVSS/gVSS.d
μ _{ANOMax,T}	Maximum specific biomass growth rate of nitrifiers at temperature T	gVSS/gVSS.d

Abbreviation	Description
ANO	Ammonia nitrifying organisms
COD	Chemical oxygen demand
E	Effluent
FSS	Fixed (inorganic) suspended solids
i	Influent
MLSS	Mixed-liquor suspended solids
MLVSS	Mixed-liquor volatile suspended solids
NIT	Nitrifying organisms
OHO	Ordinary heterotrophic organism
RBCOD	Readily biodegradable COD
SRT	Sludge retention time
SST	Secondary settling tank
TKN	Total Kjeldahl nitrogen
TSS	Total suspended solids
VSS	Volatile suspended solids



Aerobic lagoons and ponds are in many low- and medium-income countries prevailing technologies for the removal of organic matter from sewage, and faecal and septic sludge, often in combination with anaerobic and facultative ponds (photo: M. von Sperling).