10.2.1 System A1: Conventional secondary treatment

The most elementary configuration of the activated sludge system consists of a completely mixed aerobic reactor treating the influent, followed by a final settler and equipped with a gravity thickener and anaerobic digester for stabilisation of the produced excess sludge. In practice this system will also be equipped with a pre-treatment capable of removing large debris (rags, paper, plastics), sand and if required oil, fat and grease. For the design of these units refer for instance to Metcalf & Eddy (2003). For optimised system design the following data are required:

(1) Sludge age at which the system should be operated;
(2) Values of the parameters of the ideal model of the activated sludge system;
(3) Influent characteristics;
(4) Cost and financial parameters.

(1) The design sludge age:

The selected operating sludge age depends on the minimum sludge age required to:

- Obtain a substantially complete removal of organic material (incl.detergents and soaps);
- Allow development of protozoa predating on free bacteria.

When the above conditions are satisfied, a clean effluent with a low content of suspended solids and biodegradable organic material can be produced. In Chapter 3 and Appendix 3 it is demonstrated that a minimum sludge age of 2 to 3 days should be sufficient for temperatures > 14°C. The sludge age may be marginally higher if complete removal of detergents is required to avoid foaming problems.

(2) Parameters of the ideal model of the activated sludge system:

With respect to the ideal model of the activated sludge system, the following parameters are distinguished:

- Characteristics defining sludge production (Y, f_{cv} and f);
- Characteristics defining sludge composition (f_v, f_n and f_p);
- The decay constant of the active sludge (b_h), which is temperature dependent;
- The Vesilind constants defining sludge settleability (k and v_0).

In Table 10.6 the default parameter values of the ideal activated sludge model are given. The values of the settleability constants correspond to sludge with poor settling characteristics. Also included in Table 10.6 is the oxygen transfer efficiency of the surface aerators, a parameter required to estimate the use of electricity for aeration.

Table 10.6 Default values of the parameters of the activated sludge system for secondary treatment

Parameter	Symbol	Default value	Unit of measure
Sludge related parameters:			
- sludge yield	Y	0.45	mg VSS.mg^{-1} COD
- ratio COD/VSS	f_{cv}	1.50	mg COD.mg^{-1} VSS
- fraction remaining as endogenous residue	f	0.20	mg VSS. mg^{-1} VSS
Decay rate (heterotrophs)	b_h	$0.24 \cdot 1.04^{(T-20)}$	d^{-1}
Settleability parameters:	k	0.46	l.g^{-1}
	v_0	6.0	m.h^{-1}
	DSVI	120	ml.l^{-1}
Sludge composition:			
- inorganic fraction	f_v	0.70	mg VSS.mg^{-1} TSS
- nitrogen fraction	f_n	0.10	mg N.mg^{-1} VSS
- phosphorus fraction	f_p	0.025	mg P.mg^{-1} VSS
Oxygen transfer efficiency	η	$1.2 \cdot 1.03^{(T-20)}$	kg O_2.kWh^{-1}

In Table 10.7 the required data regarding the characterisation of the influent is given. The values of flow and concentration of organic material, as well as the composition in terms of non-biodegradable particulate and soluble fractions are required. To estimate the (possible) nutrient demand, the influent nitrogen and phosphorus concentrations should also be known.

Table 10.7 Waste water characteristics

Parameter	Symbol	Unit of measure
Influent flow rate	Q_i	m^3.d^{-1}
Organic material:		
- COD concentration	S_{ti}	mg COD.l^{-1}
- non biodegradable soluble fraction	f_{ns}	mg COD.mg^{-1} COD
- non biodegradable particulate fraction	f_{np}	mg COD.mg^{-1} COD
Nutrients:		
- nitrogen	N_{ti}	mg N.l^{-1}
- phosphorus	P_{ti}	mg P.l^{-1}

The activated sludge system should be designed for the lowest expected waste water temperature. Temperatures above this minimum will result in improved performance. As for industrial waste waters, the temperature of the influent is often a result of upstream process operations. Here it is important that large fluctuations in temperature are avoided (consider the implementation of a feed buffer tank) and that the temperature in the bioreactor will not exceed 40°C (35°C in case of nitrification), as this will result in massive decay of biomass.

Especially in regions with a hot climate or when concentrated waste water is treated (resulting in the generation of reaction heat), the temperature in the bioreactor can increase by a number of degrees Celsius above the influent temperature.

When necessary, influent coolers must be installed. As for the digester, this unit can be operated either on or above ambient temperature (when the combustion energy in the produced methane is used for heating). At higher temperatures, the rate of the anaerobic digestion process will increase and the required digestion volume will be reduced. However, this will be at the expense of additional investment costs for turbines, heat exchangers and control & safety equipment.

When the required data in Table 10.6 and 10.7 has been gathered, as well as the financial and costing data from Tables 10.2 to 10.4, the design optimisation of system A1 is performed according to the following procedure:

(1) For the selected sludge age determine the resulting sludge mass in the system using Eq. (3.50) and the daily excess sludge production (volatile and total) with Eq. (3.58):

$$MX_v = [(1 - f_{ns} - f_{np})\cdot(1 + f\cdot b_h\cdot R_s)\cdot Y\cdot R_s/(1 + b_h\cdot R_s) + f_{np}\cdot R_s/f_{cv}]\cdot Q_i\cdot S_{ti} \tag{3.50}$$

$$MX_t = MX_v/f_v \tag{3.51}$$

$$ME_v = MX_v/R_s \tag{3.58}$$

$$ME_t = MX_t/R_s = ME_v/f_v$$

(2) Determine the optimal sludge concentration in the reactor for which the combined construction costs of reactor and settler C_{rd} will be minimised and calculate the resulting unit volumes. I.e. minimise the following equation:

$$C_{rd} = C_r\cdot V_r + C_d\cdot V_d \tag{10.2}$$

Where the volumes of the units are given by:

$$V_r = MX_t/X_t \tag{3.55}$$

$$V_d = (S_{fd}\cdot H_d/v_0)\cdot\exp(k\cdot X_t)\cdot Q_i \tag{6.32}$$

Determine the value of the critical sludge recycling factor s_c and select an appropriate value for s (> s_c). Verify the hydraulic residence time in the settler and adapt the value of s if necessary (Section 6.3). Determine the excess sludge flow discharged from the aerobic reactor:

$$q = V_r/R_s \tag{3.16}$$

(3) Determine the optimal concentration of thickened sludge for which the construction costs of thickener and digester C_{thdi} are minimal and calculate the resulting volumes. In the optimisation procedure the following parameters are calculated as a function of the thickened sludge concentration.

$$X_{thl} = (X_{thr}/2)\cdot[1 + (1 - 4/(k\cdot X_{thr}))^{0.5}] \tag{6.18}$$

$$F_l = X_{thr}\cdot v_0\cdot(k\cdot X_{thl} - 1)\cdot\exp(-k\cdot X_{thl}) \tag{6.19}$$

$$V_{th} = S_f\cdot ME_t/F_l \tag{6.45}$$

$$q_{th} = q\cdot(X_t/X_{thr}) \tag{10.3}$$

$$V_{di} = q_{th}\cdot(20\cdot 1.1^{(T-20)} + 5) \tag{8.58}$$

$$C_{thdi} = C_{th}\cdot V_{th} + C_{di}\cdot V_{di} \tag{10.4}$$

The minimum value C_{thdi} indicates the optimal concentration to minimise the total construction costs of thickener and digester. For the optimal values, check if the hydraulic residence time in the thickener is adequate (< 1 day). If this is not the case, decrease the selected thickened sludge concentration. For the hydraulic residence time in the digester R_{di} (which depends on the temperature), calculate the digestion efficiency of active sludge and the digested sludge quantity (both total and volatile).

$R_{dp} = 36 + 0.67 \cdot T$ (8.59a)
$R_{dn} = 10 + 0.19 \cdot T$ (8.59b)
$MS_d = ME_v \cdot f_{cv} \cdot (f_{av} \cdot R_{dp} + (1 - f_{av}) \cdot R_{dn})$ (10.5)
$ME_{ve} = ME_v - MS_d / f_{cv}$ (10.6)
$ME_{te} = ME_t - MS_d / f_{cv}$ (10.7)

(4) Determine if the nutrient concentration in the influent is sufficient to cover the demand for the production of excess sludge. To calculate the mass of nitrogen and phosphorus in the excess sludge load use Eqs. (3.61 and 3.62). Take into account that in the digester, part of the nutrients contained in the excess sludge are mineralised and released into the liquid phase. After solids-liquid separation this quantity will be returned to the aeration tank. Use values of $f_n = 0.1$ kg N and $f_p = 0.025$ kg P per kg of digested excess sludge.

If the nutrient concentration in the influent is not sufficient, the quantity of nutrients to be added is calculated, otherwise the resulting nutrient effluent concentrations can be calculated. The actual nutrient demand will have a value between a maximum corresponding to the nutrient demand of the produced excess sludge and a minimum corresponding to that of the produced stabilised sludge. The maximum nutrient demand of the activated sludge process (in the secondary excess sludge) can be calculated as:

$N_l = f_n \cdot ME_v / Q_i$
$P_l = f_p \cdot ME_v / Q_i$

The minimum nutrient demand of the activated sludge process (in the stabilised sludge) is:

$N_{le} = f_n \cdot ME_{ve} / Q_i$ (10.8)
$P_{le} = f_p \cdot ME_{ve} / Q_i$ (10.9)

In practice the maximum nutrient demand will be used to calculate the addition of nutrients for systems without nutrient removal (if required), while the minimum demand is used to size nutrient removal systems.

(5) Determine the different fluxes of organic material: effluent, oxidised, digested and transformed into stabilised sludge. Furthermore define the oxygen demand (O_t), the aeration capacity to be installed and the amount of potential energy that can be generated from the methane produced during anaerobic sludge digestion.

$MS_{te} = f_{ns} \cdot S_{ti} \cdot Q_i$
$MS_o = (1 - f_{ns} - f_{np}) \cdot (1 - f_{cv} \cdot Y + f_{cv} \cdot b_h \cdot (1 - f) \cdot Y \cdot R_s / (1 + b_h \cdot R_s)) \cdot S_{ti} \cdot Q_i$
$MS_d = ME_v \cdot f_{cv} \cdot (f_{av} \cdot R_{dp} + (1 - f_{av}) \cdot R_{dn})$
$MS_{xve} = MS_{ti} - MS_{te} - MS_o - MS_d = ME_{ev} \cdot f_{cv}$

The oxygen uptake rate is calculated as the ratio between the mass flux of consumed oxygen and the aerobic reactor volume or $O_t = MS_o / V_r$. The average oxygenation capacity will be equal to the average consumption of oxygen. However, in order to be able to meet fluctuating oxygen demands, the installed capacity will have to be larger than the average capacity. The variation in oxygen demand depends on the characteristics of the waste water (variation in influent COD and flow rate) and on the system configuration (e.g. the presence of a feed buffer tank and the flow pattern in the aeration tank). In general the maximum demand rarely exceeds more than 1.5 times the average demand:

$OC = MS_o$ and $OC_{max} = 1.5 \cdot MS_o$

For a more accurate estimate of the required maximum oxygenation capacity, it will be necessary to perform dynamic simulations using the estimated variations in influent flow and organic load as input. For surface aeration, with the assumed efficiency of the aerator in terms of mass of oxygen transferred per unit of energy consumed (η), the installed average and maximum power can be calculated. The calculation of the power requirements of diffused aeration has been demonstrated in Section 3.3 and Example 7.1.

$$P_{el} = OC/\eta \text{ and } P_{max} = OC_{max}/\eta$$

The amount of methane generated will be equal to 25% of MS_d, the mass of digested COD. When the methane production is known, the electrical energy that can potentially be generated can be calculated. The value of this potential can be compared with the demand calculated above.

$$E_{el} = 5.25 \cdot R_{el} \cdot MS_d/4 \qquad (8.67)$$

(6) For the optimised unit volumes use the costing data to determine the total investment costs :

$$I = C_r \cdot V_r + C_d \cdot V_d + C_{th} \cdot V_{th} + C_{di} \cdot V_{di} + C_{ae} \cdot P_{max} \qquad (10.10)$$

(7) Estimate the factors that contribute to financial (interest rate) and operational costs (personnel, operation, maintenance, energy consumption and sludge disposal). Calculate the total annual costs and costs per unit volume of treated waste water. The annual financial costs are calculated as a fraction R of the required investment I, where the value of R is given by Eq. (10.1):

$$R = I/a_{i,n} \qquad (10.1)$$

The operational costs are composed of several factors, which can be expressed as:

$$O = (p + o + m + n) \cdot I + C_{el} \cdot P_{el} + C_h \cdot P_h + C_{sd} \cdot ME_{te}/d.s.\% \qquad (10.11)$$

Where:

O = operational costs (US\$.year^{-1})
I = total investment costs (US\$)
p = ratio between personnel and investment costs (% per year)
o = ratio between operational and investment costs (% per year)
m = ratio between maintenance and investment costs (% per year)
n = ration between insurance and investment costs (% per year)
C_{el} = cost of electrical energy (US\$.kWh^{-1})
C_h = cost of heating medium (US\$.m^3 gas)
C_{sd} = cost of sludge disposal (US\$.t^{-1} TSS)
% d.s. = percentage of dry solids in the dewatered sludge (20 - 30%)

Finally, calculate the total annual costs, which are composed of the annualised investment costs R and the annual operational costs discussed above.