

Example 10.2

Optimise the design of an activated sludge system for treatment of sewage from a city of 100,000 inhabitants. The average waste water production is $120 \text{ l.d}^{-1}.\text{hab}^{-1}$ ($Q_i = 12,000 \text{ m}^3.\text{d}^{-1}$). The characteristics of the sewage and the costing data are presented in Tables 10.8 and 10.9. The applied sludge age is 3 days.

Table 10.8 Waste water characteristics of Example 10.2

Parameter	Value	Unit of measure
Influent flow rate:	12,000	$\text{m}^3.\text{d}^{-1}$
Organic material:		
- COD concentration	650	mg COD.l^{-1}
- non biodegradable soluble fraction	0.10	-
- non biodegradable particulate fraction	0.08	-
Nutrients:		
- nitrogen	50	mg N.l^{-1}
- phosphorus	15	mg P.l^{-1}
Temperature:		
- minimum / digester	20	$^{\circ}\text{C}$

Table 10.9 Costing data of Example 10.2

Cost parameters	Value	Unit of measure
Cost per unit measure of volume/kW installed:		
C_r aeration tank	175	$\text{US}\$. \text{m}^{-3}$
C_d final settler	300	$\text{US}\$. \text{m}^{-3}$
C_{th} sludge thickener	400	$\text{US}\$. \text{m}^{-3}$
C_{di} digester	350	$\text{US}\$. \text{m}^{-3}$
C_{ae} surface aeration	3500	$\text{US}\$. \text{kW}^{-1}$
Depreciation:		
n expected lifetime	20	years
i interest rate	6%	per year
Multipliers:		
f_{ac} construction costs of additional units	1.35	(-)
f_i additional investment costs	1.6	(-)
Operational cost parameters:		
C_{el} Electrical energy	0.15	$\text{US}\$. \text{kWh}^{-1}$
C_{sd} Sludge disposal	200	$\text{US}\$. \text{ton}^{-1}$ sludge
C_h Heating energy	0.35	$\text{US}\$. \text{m}^3$ gas
p / o Personnel / operation	3% / 1% per year	of investment
m / n Maintenance / insurance	2% / 0.3% per year	of investment

Step 1: Determine the sludge mass in the system

For the given characteristics and conditions:

$$\begin{aligned}
 MX_a &= [(1 - f_{ns} - f_{np}) \cdot Y \cdot R_s / (1 + b_h \cdot R_s)] \cdot MS_{ti} \\
 &= (1 - 0.10 - 0.08) \cdot 0.45 \cdot 3 / (1 + 0.24 \cdot 3) \cdot 12,000 \cdot 0.65 = 5020 \text{ kg VSS} \\
 MX_v &= [(1 - f_{ns} - f_{np}) \cdot (1 + f \cdot b_h \cdot R_s) \cdot Y \cdot R_s / (1 + b_h \cdot R_s) + f_{np} \cdot R_s / f_{cv}] \cdot Q_i \cdot S_{ti} \\
 &= [(1 - 0.10 - 0.08) \cdot (1 + 0.2 \cdot 0.24 \cdot 3) \cdot 0.45 \cdot 3 / (1 + 0.24 \cdot 3) + 0.08 \cdot 3 / 1.5] \cdot 12,000 \cdot 0.65 \\
 &= 6991 \text{ kg VSS} \\
 \\
 MX_t &= MX_v / f_v = 6067 / 0.7 = 9987 \text{ kg TSS} \\
 ME_v &= MX_v / R_s = 6990 / 3 = 2330 \text{ kg VSS} \cdot \text{d}^{-1} \\
 ME_t &= ME_v / f_v = 2331 / 0.7 = 3329 \text{ kg TSS} \cdot \text{d}^{-1} \\
 f_{av} &= MX_a / MX_v = 5020 / 6990 = 0.72 \text{ kg VSS} \cdot \text{kg}^{-1} \text{TSS}
 \end{aligned}$$

Step 2: Dimensioning the reactor - settler system

For the calculated sludge mass, optimise the volumes of reactor and settler using the minimal cost criterion, taking the sludge concentration in the reactor as the independent variable. Check the hydraulic residence time in the settler for the critical recirculation factor. Using Eqs. (3.55, 6.32 and 10.2), calculate the biological reactor and settler volume and hence the construction costs as a function of X_t :

$$\begin{aligned}
 V_r &= MX_t / X_t = 9987 / X_t && (3.55) \\
 V_d &= (S_{id} \cdot H_d / v_0) \cdot \exp(k \cdot X_t) \cdot Q_i = 2 \cdot 4 / 6 \cdot \exp(0.46 \cdot X_t) \cdot 12,000 && (6.32) \\
 C_{rd} &= C_r \cdot V_r + C_d \cdot V_d = 175 \cdot V_r + 300 \cdot V_d && (10.2)
 \end{aligned}$$

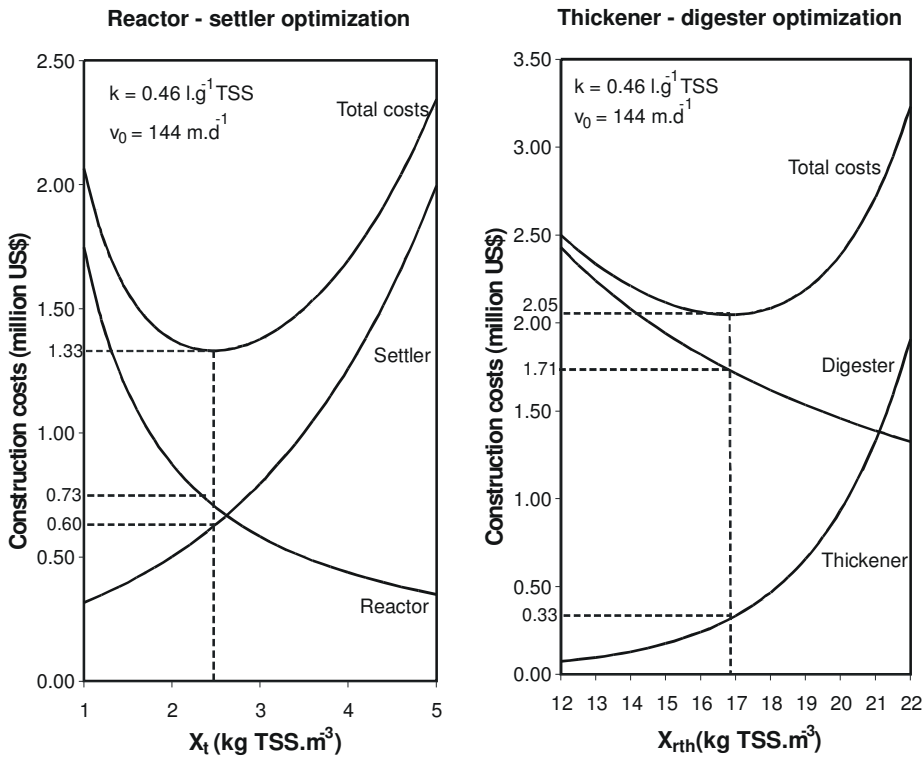


Figure 10.3 Graphical optimisation of system configuration A1

In Fig. 10.3 the calculated construction costs of the Example 10.2 are shown. It can be observed that the minimum value is obtained for a sludge concentration X_t of 2.4 g TSS.l^{-1} , where $V_r = 4161 \text{ m}^3$ and $V_d = 2011 \text{ m}^3$, respectively. The sludge volume is $2.4 \cdot 120 = 288 \text{ ml}$: i.e. sufficient for zone settling. For the optimum concentration, calculate with the aid of Eq. (6.37b) or Fig. 6.9 that for $k \cdot X_t = 1.1$ the critical recirculation factor $s_c = 0.35$. This results in a hydraulic residence time in the final settler of:

$$R_{hd} = v_d = V_d / (Q_i \cdot (1 + s_c)) = 2011 / (500 \cdot 1.35) = 3.0 \text{ h}$$

This value is acceptable, especially as in practice the applied sludge recycle factor s will be larger than the critical recirculation rate s_c , e.g. for $s = 1.0$ the value of $R_{hd} = 2$ hours.

Step 3: Dimensioning the thickener - digester system

For the calculated excess sludge production optimise the volumes of thickener and anaerobic digester using the minimal cost criterion, taking the thickened sludge concentration as the independent variable.

$$X_{thl} = (X_{thr}/2) \cdot [1 + (1 - 4/(k \cdot X_{thr}))^{0.5}] = (X_{thr}/2) \cdot [1 + (1 - 4/(0.46 \cdot X_{thr}))^{0.5}] \quad (6.18)$$

$$F_l = X_{thr} \cdot V_0 \cdot (k \cdot X_{thl} - 1) \cdot \exp(-k \cdot X_{thl}) = X_{thr} \cdot 6 \cdot (0.46 \cdot X_{thl} - 1) \cdot \exp(-0.46 \cdot X_{thl}) \quad (6.19)$$

$$V_{th} = S_r \cdot ME_l / F_l = 1.5 \cdot 3329 / F_l \quad (6.45)$$

$$q_{th} = q \cdot (X_t / X_{thr}) = 1387 \cdot (2.4 / X_{thr}) \quad (10.3)$$

$$V_{di} = q_{th} \cdot (20 \cdot 1.1^{(T-20)} + 5) = q_{th} \cdot 25 \quad (8.58)$$

$$C_{thdi} = C_{th} \cdot V_{th} + C_{di} \cdot V_{di} = 400 \cdot V_{th} + 350 \cdot V_{di} \quad (10.4)$$

In Fig. 10.3 it can be observed that for the conditions specified in Example 10.2, the combined construction costs of thickener and digester have a minimum value for a thickened excess sludge concentration $X_{thr} = 17 \text{ g TSS.l}^{-1}$. For this value of X_{thr} , the volumes of thickener and digester are $V_{th} = 832 \text{ m}^3$ and $V_{di} = 4896 \text{ m}^3$ respectively. The excess sludge flow from the aerobic reactor is equal to $V_r / R_s = 4.161/3 = 1387 \text{ m}^3 \cdot \text{d}^{-1}$. The hydraulic residence time in the thickener will be $24 \cdot 832 / 1387 = 14$ hours, an acceptable value. As for the efficiency of the anaerobic sludge digestion:

$$R_{dp} = (36 + 0.67 \cdot T) / 100 = 0.49$$

$$R_{dn} = (10 + 0.19 \cdot T) / 100 = 0.14$$

Thus, for the active sludge fraction calculated in step 1 as $f_{av} = 0.72$, the digested sludge mass will be:

$$\begin{aligned} MS_d &= ME_v \cdot f_{cv} \cdot (f_{av} \cdot R_{dp} + (1 - f_{av}) \cdot R_{dn}) \\ &= 2330 \cdot 1.5 \cdot (0.72 \cdot 0.50 + 0.28 \cdot 0.13) = 1376 \text{ kg COD} \cdot \text{d}^{-1} \end{aligned}$$

Now the mass of stabilised sludge is calculated as:

$$ME_{ve} = ME_v - MS_d / f_{cv} = 2330 - 1376 / 1.5 = 1413 \text{ kg VSS} \cdot \text{d}^{-1}$$

$$ME_{te} = ME_t - MS_d / f_{cv} = 3329 - 1376 / 1.5 = 2412 \text{ kg TSS} \cdot \text{d}^{-1}$$

It is assumed that the inorganic solids will not dissolve into the liquid phase during digestion. Therefore the volatile fraction in the stabilised sludge will decrease from 70% in the thickened excess sludge to $ME_{ve} / ME_{te} = 58\%$ in the stabilised sludge.

Step 4: Nutrient concentrations

The daily volatile stabilised sludge production $ME_{ve} = 1413 \text{ kg VSS.d}^{-1}$. This sludge production will require $0.1 \cdot 1413 = 141 \text{ kg N.d}^{-1}$ and $0.025 \cdot 1413 = 35 \text{ kg P.d}^{-1}$. Divided by the influent flow this amounts to a concentration of 11.8 mg N.l^{-1} and 2.9 mg P.l^{-1} influent. Thus there will remain 38.2 mg N.l^{-1} in the effluent, when it is assumed that nitrification will not develop. With respect to phosphorus, the effluent concentration $P_{te} = 15 - 2.9 = 12.1 \text{ mg P.l}^{-1}$ in the form of phosphate. Nutrient removal in this process configuration is very limited: 76 % of the influent nitrogen load and 81 % of the influent phosphorus load will leave with the effluent.

Step 5: Process fluxes

The oxygen consumption for the specified sludge age is calculated as:

$$\begin{aligned} MO_c &= (1 - f_{ns} - f_{np}) \cdot (1 - f_{cv} \cdot Y + f_{cv} \cdot (1 - f) \cdot b_h \cdot Y \cdot R_s / (1 + b_h \cdot R_s)) \cdot Q_i \cdot S_{ii} \\ &= (1 - 0.10 - 0.08) \cdot (1 - 1.5 \cdot 0.45 + 1.5 \cdot 0.8 \cdot 0.24 \cdot 0.45 \cdot 3 / (1 + 0.24 \cdot 3)) \cdot 12,000 \cdot 0.65 \\ &= 3524 \text{ kg.d}^{-1} \end{aligned}$$

For the assumed aeration efficiency η of $1.2 \text{ kg O}_2.\text{kWh}^{-1}$, this represents an oxygen demand of $3524/1.2 = 2926 \text{ kWh.d}^{-1}$ and an average net power consumption of $2926/24 = 122 \text{ kW}$. It can be verified that the dissipated energy ($122,000/4161 = 29 \text{ W.m}^{-3}$) is more than sufficient to maintain the sludge in suspension. The average oxygen uptake rate is calculated as the ratio between the total amount of consumed oxygen and the aerated reactor volume: $3524/4161 = 0.85 \text{ kg O}_2.\text{m}^{-3}.\text{d}^{-1}$ or $35.3 \text{ mg O}_2.\text{l}^{-1}.\text{h}^{-1}$. In practice the installed aeration capacity will be larger to cover peak oxygen demands. An additional 50% capacity results in an installed capacity of 184 kW.

The amount of digested COD MS_d is equal to $1376 \text{ kg COD.d}^{-1}$ or $1376/4 = 344 \text{ kg CH}_4.\text{d}^{-1}$, which according to Eq. (8.67) allows a potential power generation of: $ME_{el} = 5.25 \cdot R_{el} \cdot MS_d / f_{cv} = 70 \text{ kW}$. The potential power generation represents 57% of the average energy demand for aeration (122 kW). Knowing that the mass of volatile stabilised sludge ($1413 \text{ kg VSS.d}^{-1}$) has a COD value of $1.5 \cdot 1413 = 2120 \text{ kg COD.d}^{-1}$, the fluxes of organic material as fraction of the applied organic load MS_{ii} can be summarised as:

- Effluent COD =	780 kg COD.d ⁻¹	(= 10%)
- Oxidised COD =	3524 kg COD.d ⁻¹	(= 45%)
- Digested COD =	1376 kg COD.d ⁻¹	(= 18%)
- Excess sludge COD =	2120 kg COD.d ⁻¹	(= 27%)

Step 6: Determine the total investment costs

The construction costs include the construction of the four main units and the acquisition and installation of aeration equipment. The minimum value of the construction costs can be determined from the calculated volumes and the unit price of each unit type, as well as the price per kW of installed aeration capacity. Using the factor f_{ac} , the construction costs of the units not explicitly considered are estimated. Finally, using factor f_i , the additional costs of Table 10.1 are accounted for. The results are shown in Table 10.10.

Table 10.10 Total investment costs of system configuration A1

Unit	Construction costs (US\$)	% of volume	Fraction of I
Reactor	730,000	32%	8%
Settler	600,000	19%	7%
Thickener	330,000	8%	4%
Digester	1,710,000	41%	20%
Aeration	620,000	-	7%
Subtotal main units	4,010,000	-	46%
Other units	1,400,000	-	16%
Additional costs	3,250,000	-	38%
Total investment (I)	8,660,000	-	100%

Step 7: Determine the cost of financing, operational costs and total costs

The investment value can be annualised and transformed into net present value. Under the conditions of Example 10.2 (i.e. interest rate $i = 6\%$ and expected lifetime $n = 20$ years), the annual costs will be 8.7% of the total investment costs for a period of 20 years. Thus an annual financing cost of $\text{US\$ } 0.087 \cdot 8,660,000 = \text{US\$ } 760,000$ per year or $\text{US\$ } 7.6$ per capita per year. For the daily per capita contribution of 120 litre, the cost per unit volume of treated waste water is $7.6 / (0.12 \cdot 365) = \text{US\$ } 0.17 \text{ m}^{-3}$. In the absence of a more detailed analysis, the annual costs of personnel, operation, maintenance and insurance can be estimated as a percentage of the investment. These costs do not include costs of energy for aeration, sludge disposal and heating (the latter is not required in this example). In Table 10.11 the annualised investment and operational costs are presented.

Table 10.11 Annualised investment and operational costs of system configuration A1

Cost item	Annual costs (US\$.year ⁻¹)	Costs per m ³ (US\$ cent)	Cost per P.E. (US\$ cent)	Percentage (%)
Investment costs	760,000	17.4	7.6	46
Operational costs	890,000	20.2	8.8	54
- aeration	160,000	3.7	1.6	10
- sludge disposal	190,000	4.0	1.8	11
- personnel	260,000	5.9	2.6	16
- operation	90,000	2.0	0.9	5
- maintenance	170,000	3.9	1.7	11
- insurance	30,000	0.6	0.3	2
Total costs	1,650,000	37.5	16.4	100

Although in practice the actual numbers may deviate from those adopted in the example, invariably the annualised investment costs represent the largest cost component (in this case 46%). On the other hand, the costs of aeration are in reality a less important factor in the operational costs than generally perceived. Other operational costs, especially costs of sludge disposal and personnel will be more important.

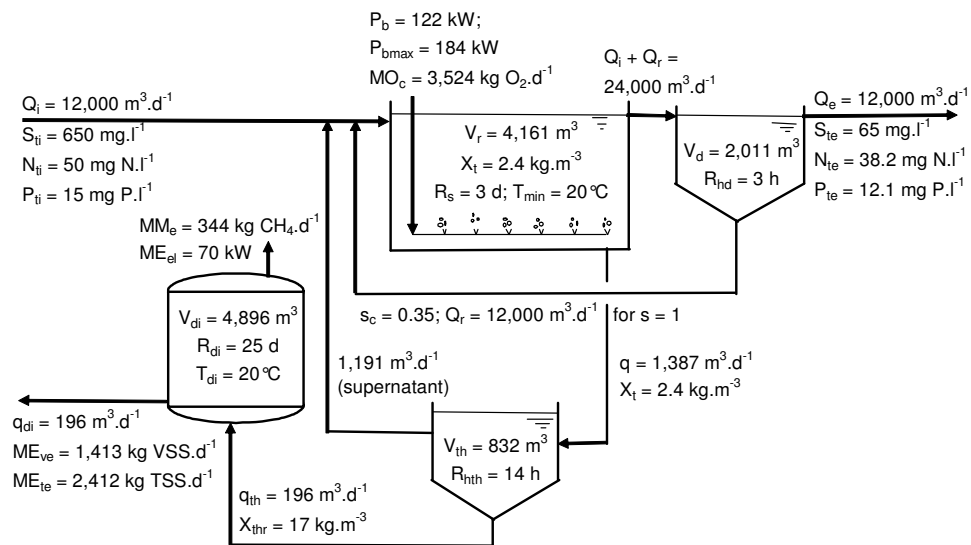


Figure 10.4 Schematic flow diagram of the optimised design of configuration A1

Step 8: Schematic diagram of the system design

In Fig. 10.4 a schematic overview is given of the optimised design results of the wastewater treatment system discussed in Example 10.2. In this figure all the main parameters and fluxes calculated in steps 1 to 7 above are indicated. Finally, in Tables 10.14 to 10.20 at the end of Section 10.2.3, the configurations for secondary treatment A1 and A2 are compared with configuration B1, anaerobic pre-treatment followed by nitrification. In these tables different aspects of the system designs will be evaluated: i.e. (1) concentrations of organic material, nitrogen and phosphorus in influent and effluent, (2) unit sizing, (3) values of interconnecting flows, (4) applied process rates, (5) sludge concentrations in the main units, (6) fluxes in units and of material, and (7) costs of the system.