Example 10.6

For the same conditions as specified in Tables 10.6 and 10.7, determine the optimum UCT configuration in order comply with the following effluent criteria: N_{ad} = 2 mg N.l^{-1}, P_{te} = 2 mg P.l^{-1} and N_{te} =10 mg N.l^{-1}. The following additional data are given:

- b_{p20} = 0.04 d^{-1}	- f_{pd} = 0.8
- f_{ep} = 0.25	- K_c = 0.06 l.mg^{-1} VSS.d^{-1}
- f_{vp} = 0.46	- f_{pp} = 0.38 mg P.mg^{-1} VSS

Step 1: Establish the value of R_s to obtain complete or maximum nutrient removal

The following values relevant for phosphorus removal are selected: N = 2, r = 1 and f_{an} = 0.10.

(a) Phosphorus removal

Follow the procedure presented in Section 5.1.3 and calculate as a function of the sludge age the following parameters:

1. Calculate the concentration of organic material sequestered by the bio-P organisms;
2. Using this value calculate the production of bio-P organisms
3. Determine the "normal" sludge concentration, based on the amount of non-sequestered organic material leaving the anaerobic reactor;
4. Calculate the concentration of the other sludge components: endogenous residue of both PAO and the normal active sludge and the inert sludge
5. Calculate the removal of phosphorus and compare this value with the desired influent concentration of phosphorus in the influent

(b) Nitrogen removal

Follow the procedure outlined in Example 10.5 and calculate as a function of the sludge age the following parameters:

1. The nitrification capacity;
2. The values of the different anoxic sludge mass fractions;
3. The denitrification capacity and compare this value with the nitrification capacity;
4. Based on these data determine the concentration of nitrogen in the effluent (ammonium, organic nitrogen and nitrate).

It can be established that for a sludge age R_s = 11 days, it is possible to comply with the nitrogen and phosphorus effluent criteria. Using this value all the main system parameters are calculated. The calculations for R_s = 11 days are presented below: the effect of release of organic nitrogen to the liquid phase during anaerobic digestion has already been included. As for the anaerobically released phosphorus, it is assumed that this will be chemically precipitated during dewatering of the digested sludge (this will not be discussed here: refer to Example 5.4). As a first step, the amount of COD sequestered by the bio-P organism in the anaerobic zone is determined for the specified conditions. Using the iterative procedure presented in Section 5.1.3, the residual concentration in the anaerobic zone S_{bsN} is calculated as 16.6 mg COD.l^{-1} (for N = 2). The sequestered COD concentration is:

$$S_{seq} = S_{bsi} - (r + 1)/r \cdot S_{bsN} = 0.2 \cdot (1 - 0.10 - 0.08) \cdot 650 - 2/1 \cdot 16.6 = 84 \text{ mg COD.l}^{-1}$$

This is the concentration of influent COD used for the production of bio-P organisms and therefore is no longer available for the production of “normal” sludge. The concentration of COD available for normal sludge is $S_{bi}' = S_{bi} - S_{seq} = 533 - 98 = 435$ mg COD.l^{-1}. Now the different sludge mass fractions can be calculated:

$C_{rh} = Y\cdot R_s/(1 + b_h\cdot R_s) = 0.45\cdot 11/(1+0.24\cdot 11) = 1.36$
$C_{rp} = Y\cdot R_s/(1 + b_p\cdot R_s) = 0.45\cdot 11/(1+0.04\cdot 11) = 3.44$

$MX_{ap} = C_{rp}\cdot MS_{seq} = 3.44\cdot 0.084\cdot 12{,}000 = 3457$ kg VSS
$MX_{ep} = f_{ep}\cdot b_p\cdot R_s\cdot MX_{ap} = 0.25\cdot 0.04\cdot 11\cdot 3457 = 380$ kg VSS
$MX_a = C_{rh}\cdot MS_{bi}' = 1.36\cdot 0.435\cdot 12{,}000 = 7332$ kg VSS
$MX_e = f\cdot b_h\cdot R_s\cdot MX_a = 0.2\cdot 0.24\cdot 11\cdot 7332 = 3871$ kg VSS
$MX_i = f_{ns}\cdot R_s/f_{cv}\cdot MS_{ti} = 0.08\cdot 11/1.5\cdot 0.650\cdot 12{,}000 = 4576$ kg VSS
$MX_v = MX_{ap} + MX_{ep} + MX_a + MX_e + MX_i = 19{,}617$ kg VSS
$MX_t = MX_{ap}/0.46 + (MX_{ep} + MX_a + MX_e + MX_i)/f_v = 30{,}601$ kg TSS

The biological removal of phosphorus can be calculated as:

$MP_l = 0.38\cdot MX_{ap}/R_s + 0.025\cdot (MX_v - MX_{ap})/R_s = 119 + 37 = 156$ kg P.d^{-1} and

$P_l = MP_l/Q_i = 156/12{,}000 = 13.0$ mg P.l^{-1}

It can be observed that the phosphorus demand for the production of excess sludge is somewhat lower than the concentration available in the influent (P_{ti} = 15 mg P.l^{-1}). If not enough phosphate is available in the influent, then there would have been a concomitant decrease in the production of bio-P organisms and more non-sequestered material would have been available for the “normal” sludge. The concentration of phosphate in the effluent is equal to:

$P_{te} = P_{ti} - P_l = 15.0 - 13.0 = 2.0$ mg P.l^{-1}

It can be concluded that the residual phosphorus concentration meets the specified effluent limit. If the concentration of phosphorus in the effluent is not low enough, various measures could be taken to increase the biological removal of phosphorus:

- Increase the anaerobic sludge fraction f_{an} or increase the recirculation rate "r";
- Increase the number of anaerobic reactors N
- Reduce the sludge age (at the expense of nitrogen removal) or a combination of these actions.

As the viability of biological phosphorus removal for R_s = 11 days has been demonstrated, the following step is to calculate the nitrogen removal. For the sludge age of 11 days, the maximum allowed non-aerated sludge mass fraction is calculated with Eq. (4.40) as:

$f_m = 1 - (1 + K_n/N_{ad})\cdot (b_n + 1/R_s)/\mu_m$
$= 1 - (1 + 1/2)\cdot (0.04 + 1/11)/0.3 = 0.35$

So $f_{ae} = 1 - f_m = 0.65$. As the value of the anaerobic mass fraction $f_{an} = 0.10$, the maximum combined value of the anoxic mass fractions $f_{x1} + f_{x3} = f_m - f_{an} = 0.35 - 0.10 = 0.25$. For $f_{x1} = 0.2$ and $f_{x3} = 0.05$ the nitrogen effluent limits will be met. $ME_v = 19{,}617 / 11 = 1783$ kg VSS.d^{-1} and the daily nitrogen demand for excess sludge production is equal to:

$MN_l \quad = f_n \cdot ME_v = 0.1 \cdot 1783 = 178$ kg N.d^{-1}

In the sludge digester 595 kg VSS.d^{-1} of volatile sludge is digested. Thus the amount of stabilised excess sludge $ME_{ve} = 1783 - 595 = 1188$ kg VSS.d^{-1}. $MN_{le} = 0.1 \cdot 1188 = 119$ kg N.d^{-1}, which represents an influent concentration of $N_{le} = MN_{le}/Q_i = 119/12{,}000 = 9.9$ mg N.l^{-1}. For the residual organic nitrogen and ammonium concentrations of 2 mg N.l^{-1} each, the required nitrification capacity can be calculated as:

$N_c \quad = N_{ti} - N_{le} - N_{oe} - N_{ad} = 50 - 9.9 - 2 - 2 = 36.1$ mg N.l^{-1}

In this example it is assumed that (conservatively) only 80% of the bio-P organisms are capable of denitrification. Therefore, in order to evaluate the extent of denitrification, it will be necessary to differentiate in the following influent COD fractions:

$S_{bsp} = 84$ mg COD.l^{-1} $\rightarrow f_{bsp} = 84/107 = 0.79$
$S_{bsh} = 107 - 84 = 23$ mg COD.l^{-1} $\rightarrow f_{bsh} = 23/107 = 0.21$
$S_{bp} = 84$ mg COD.l^{-1} $\rightarrow f_{bp} = 84/533 = 0.16$
$S_{bh} = 533 - 84 = 449$ mg COD.l^{-1} $\rightarrow f_{bh} = 449/533 = 0.84$

Now the denitrification capacities can be calculated with Eqs. (5.9 and 5.11):

$$\begin{aligned} D_{C1} &= [f_{dn} \cdot (f_{bsp} \cdot f_{pd} + f_{bsh}) \cdot f_{sb} + K_2 \cdot f_{x1} \cdot (C_{rh} \cdot f_{bh} + C_{rp} \cdot f_{bp} \cdot f_{pd})] \cdot S_{bi} \\ &= [0.11 \cdot (0.79 \cdot 0.8 + 0.21) \cdot 0.2 + 0.10 \cdot 0.2 \cdot (1.36 \cdot 0.84 + 3.44 \cdot 0.16 \cdot 0.8)] \cdot 533 = 27.0 \text{ mg N.l}^{-1} \end{aligned}$$

$$\begin{aligned} D_{C3} &= K_3 \cdot f_{x3} \cdot (C_{rh} \cdot f_{bh} + C_{rp} \cdot f_{bp} \cdot f_{pd}) \cdot S_{bi} \\ &= 0.08 \cdot 0.05 \cdot (1.36 \cdot 0.84 + 3.44 \cdot 0.16 \cdot 0.8) \cdot 533 = 3.1 \text{ mg N.l}^{-1} \end{aligned}$$

$D_C \quad = D_{c1} + D_{c3} = 27.0 + 3.0 = 30.1$ mg N.l^{-1}

It can be checked that the available nitrate (N_{av}) is larger than the denitrification capacity for both anoxic zones so that the effluent nitrate concentration can be calculated as:

$N_{ne} \quad = N_c - D_c = 36.1 - 30.1 = 6$ mg N.l^{-1} and $N_{te} = N_{ne} + N_{oe} + N_{ad} = 6 + 2 + 2 = 10$ mg N.l^{-1}

In order to prevent the recycling of nitrate from the anoxic- to the anaerobic reactor, which would reduce the amount of VFA available to the bio-P organisms, the value of the recirculation factor should be reduced to a value of a = 2.75. It can be verified that N_{av1} is now indeed equal to D_{C1}:

$$\begin{aligned} N_{av1} &= a/(a+s+1) \cdot N_c + s \cdot N_{ne} \\ &= 2.75/(2.75+1+1) \cdot 36.1 + 1 \cdot 6 = 27 \text{ mg N.l}^{-1} \end{aligned}$$

Steps 2-9: Optimise the system C2 (UCT configuration)

Once the sludge age and the division of the sludge mass in aerobic, anoxic and anaerobic fractions has been determined, the system can be further optimised using the procedure outlined in Example 10.2.

Due to the fact that the sludge concentration in the anaerobic zone is a factor r/(1+r) smaller than in the other reactors, the volumetric fraction will have to be a factor (1+r)/r larger than the specified anaerobic sludge mass fraction f_{an}. Thus the total volume of a UCT system will be a factor $(1+f_{an}/r)$ larger than a system with an equivalent sludge mass but with a uniform concentration. In the example at hand with $f_{an} = 0.10$ and r = 1, the volume of the UCT system will be a factor (1+ 0.10/1) = 1.10 or 10 percent larger

Nutrients will be released during the anaerobic digestion of the produced excess sludge. In the case of nitrogen, this effect can be compensated by an increase of the sludge age. However, the amount of phosphorus released is too large to be handled in the same way. The daily excess sludge quantities produced and stabilised for a sludge age of 11 days are 1783 kg and 1188 kg $VSS.d^{-1}$ respectively. The volatile excess sludge contains 156 kg $P.d^{-1}$, representing a concentration of 13.0 mg $P.l^{-1}$ in the influent.

Assuming that during anaerobic digestion the PAO are destructed in the same way as the non PAO organisms and that the stabilised sludge will have a phosphorus content of 0.025 mg $P.mg^{-1}VSS$, the amount of phosphorus in the stabilised sludge will be only 29.7 kg $P.d^{-1}$, resulting in a potential release of 156 - 29.7 = 126.5 kg $P.d^{-1}$, representing 10.5 mg $P.l^{-1}$. This release of phosphate is partly compensated by the formation of metal-phosphate complexes that precipitate on the sludge.

However, as it concerns such a large part of the phosphorus removed from the influent (10.5 of the 13.0 mg $P.l^{-1}$ removed), often chemical precipitation with metal salts is applied either to the influent or the effluent of the digester, so that all phosphorus released is precipitated and will not be returned to the activated sludge system. Taking into account that the flow of digested sludge will be small (in the example q_{di} = 166 $m^3.d^{-1}$), this will be a relatively small-scale operation.

In Table 10.22 the annualised costs of system configuration C2 are shown, while in Figs. (10.13 and 10.14) and Tables 10.23 to 10.29 the optimised solution is further specified and compared to that of configuration C1.

Table 10.22 Annualised investment and operational costs of system configuration C2

Cost item	Annual costs ($US\$.year^{-1}$)	Costs per m^3 (US$ cent)	Cost per PE (US$ cent)	Percentage (%)
Investment costs	990,000	22.6	9.9	48
Operational costs	1,090,000	24.9	10.9	52
- aeration	220,000	5.0	2.2	11
- sludge disposal	160,000	3.7	1.6	8
- personnel	340,000	7.8	3.4	16
- operation	110,000	2.5	1.1	5
- maintenance	230,000	5.3	2.3	11
- insurance	30,000	0.7	0.3	1
Total costs	2,080,000	47.5	20.8	100

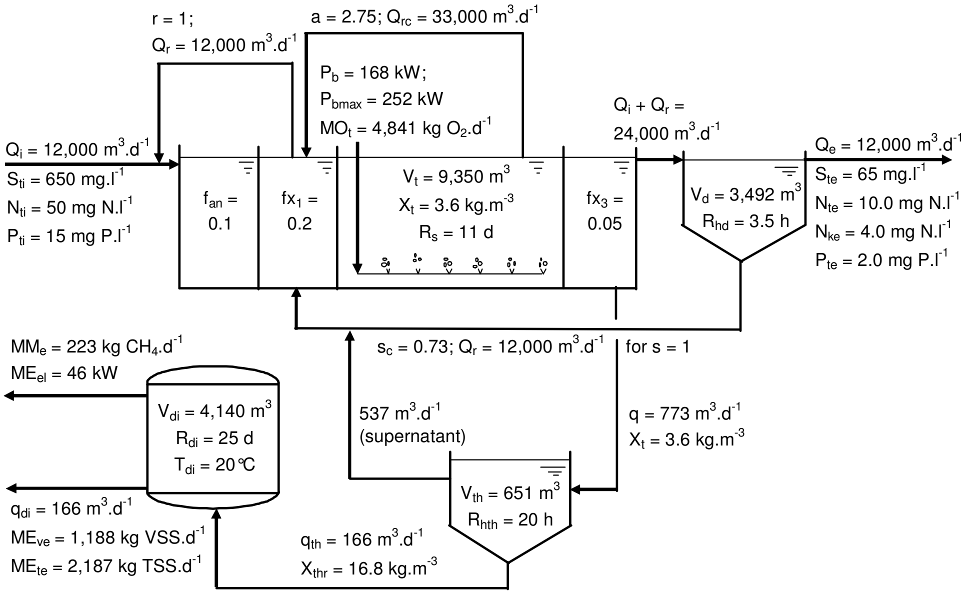

Figure 10.13 Schematic flow diagram of the optimised design of configuration C2