

Remark for studying the calculations:

- at the end of the semester you should be able to perform all exercises by yourself
- you do not need to know formula's by heart but should be able to apply them

Lesson 2

- Design of organic matter removal
- Sludge treatment

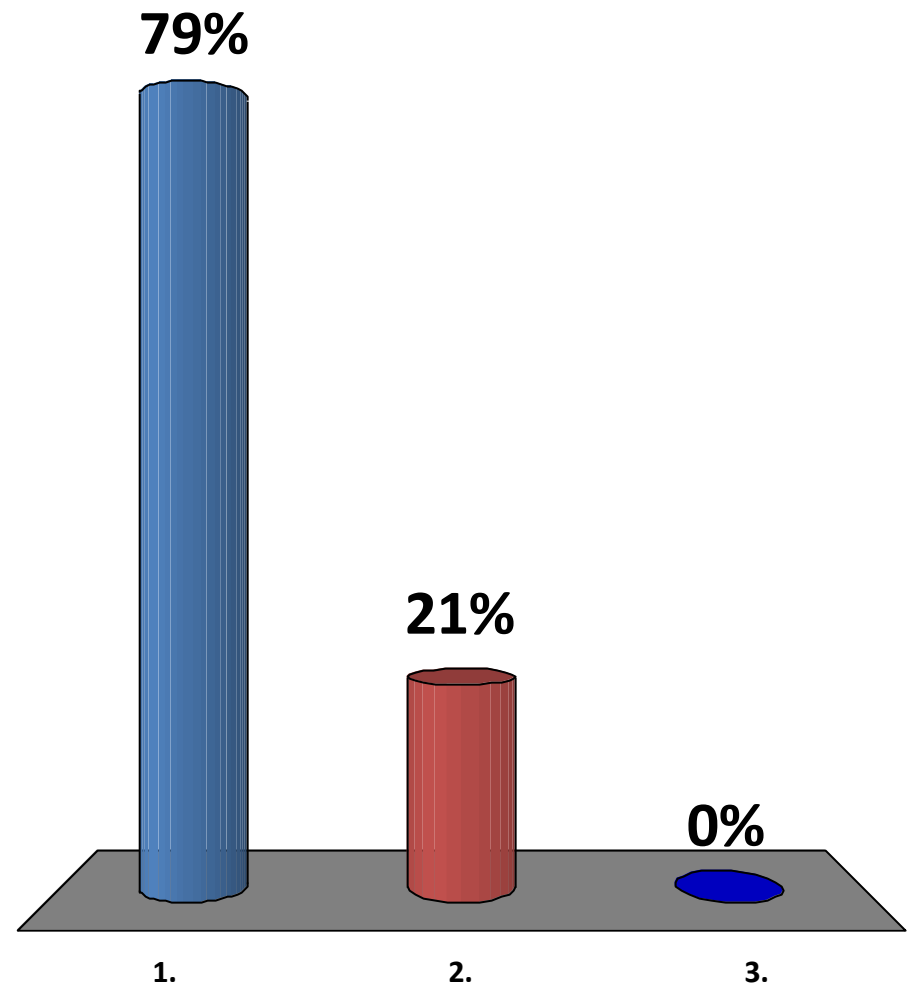
Dr. Jan Arends

Jan.Arends@ugent.be

4/11/2015

Kies uw richting

1. Chemie & Voeding
2. Milieutechnologie
3. Andere



Wrap-up

At the end of the semester you can:

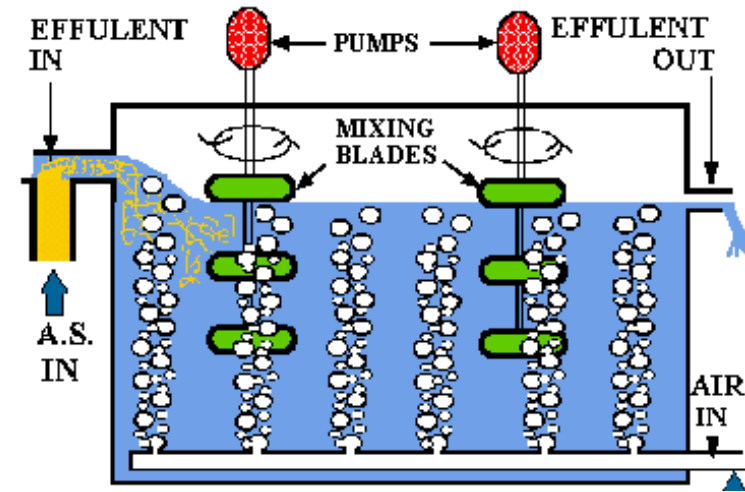
- Make a schematic drawing of a WWTP
- Set-up and solve a mass-balance of a WWTP or its unit processes
- Calculate operational parameters based on biokinetic values
- Estimate operational costs/gain of a WWTP

Biokinetic values

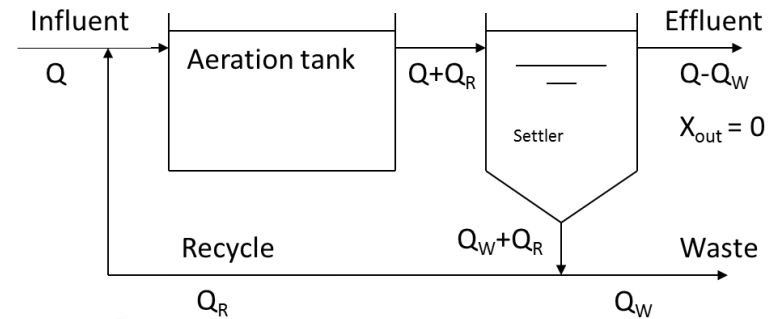
- Microbial community: biokinetic constants
 - Y^{\max} : yield (g VSS/g substrate)
 - b : decay coefficient
 - q_{\max} : maximum growth rate
 - K_s : substrate affinity coefficient
- Determined by lab scale reactors and pilot plants

3 types

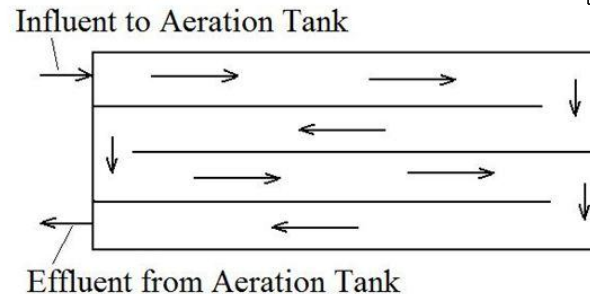
- Completely mixed, no recycle



- Completely mixed, recycle



- Plug flow



Serpentine Pattern, 'Plug Flow'
Activated Sludge Aeration Tank

Equations

<i>Characteristics</i>	<i>Completely mixed no recycle system</i>	<i>Completely mixed recycle system</i>	<i>Plug flow system</i>
<i>Waste removal efficiency</i>	$E = \frac{100(S_0 - S)}{S_0}$	$E = \frac{100(S_0 - S)}{S_0}$	$E = \frac{100(S_0 - S_e)}{S_0}$
<i>Effluent waste concentration (g/L)</i>	$S = \frac{K_s(1 + b\theta_x)}{\theta_x(Y_{COD}^{max}q_{max} - b) - 1}$	$S = \frac{K_s(1 + b\theta_x)}{\theta_x(Y_{COD}^{max}q_{max} - b) - 1}$	No explicit solution for S_e
<i>Biomass concentration in reactor (g/L)</i>	$X = \frac{Y_{COD}^{max}(S_0 - S)}{1 + b\theta_x}$	$X = \frac{Y_{COD}^{max}(S_0 - S)}{(1 + b\theta_x)\bar{t}}$	$X = \frac{Y_{COD}^{max}(S_0 - S)\theta_x}{(1 + b\theta_x)\bar{t}}$
<i>Excess biomass production rate (kg/d for Q in m³/d; S₀ and S_e in g/L)</i>	$\Delta X = \frac{Y_{COD}^{max}Q(S_0 - S)}{1 + b\theta_x}$	$\Delta X = \frac{Y_{COD}^{max}Q(S_0 - S)}{1 + b\theta_x}$	$\Delta X = \frac{Y_{COD}^{max}Q(S_0 - S_e)}{1 + b\theta_x}$
<i>Sludge growth rate (d⁻¹)</i>	$\mu = \frac{1}{\theta_x} = \frac{Y_{COD}^{max}q_{max}S}{K_s + S} - b$	$\mu = \frac{1}{\theta_x} = \frac{Y_{COD}^{max}q_{max}S}{K_s + S} - b$	$\mu = \frac{1}{\theta_x} = \frac{Y_{COD}^{max}q_{max}(S_0 - S_e)}{(S_0 - S_e) + (1 + R)K_s \ln(S_0 / S_e)} - b$
			where $S_1 = \frac{S_0 + RS_e}{1 + R}$
<i>Limiting or minimum biological solids retention time (d)</i>	$\theta_x^{min} = \frac{1}{Y_{COD}^{max}q_{max} - b}$	$\theta_x^{min} = \frac{1}{Y_{COD}^{max}q_{max} - b}$	Not mathematically determined
<i>Reactor volume (m³)</i>	$V = \frac{Y_{COD}^{max}Q\theta_x(S_0 - S)}{X(1 + b\theta_x)}$	$V = \frac{Y_{COD}^{max}Q\theta_x(S_0 - S)}{X(1 + b\theta_x)}$	$V = \frac{Y_{COD}^{max}Q\theta_x(S_0 - S)}{X(1 + b\theta_x)}$
<i>Oxygen demand (kg/d)</i>	$OD = Q(S_0 - S) - 1.33\Delta X$	$OD = Q(S_0 - S) - 1.33\Delta X$	$OD = Q(S_0 - S_e) - 1.33\Delta X$

Exercise P.28

Wastewater from a starch factory is treated in a completely mixed system with recycling.

Operational:

- $Q = 100 \text{ m}^3/\text{d}$
- $S_0 = \text{bCOD} = 1.0 \text{ g/L}$
- $S_{\text{effluent}} = 15 \text{ mg bCOD/L (10 mg BOD}_5\text{/L)}$.

Biological:

- $Y_{\text{cod}}^{\text{max}} = 0.44$
- $b = 0.02 \text{ d}^{-1}$
- $q_{\text{max}} = 2.05 \text{ d}^{-1}$
- $K_S = 0.076 \text{ g/L}$

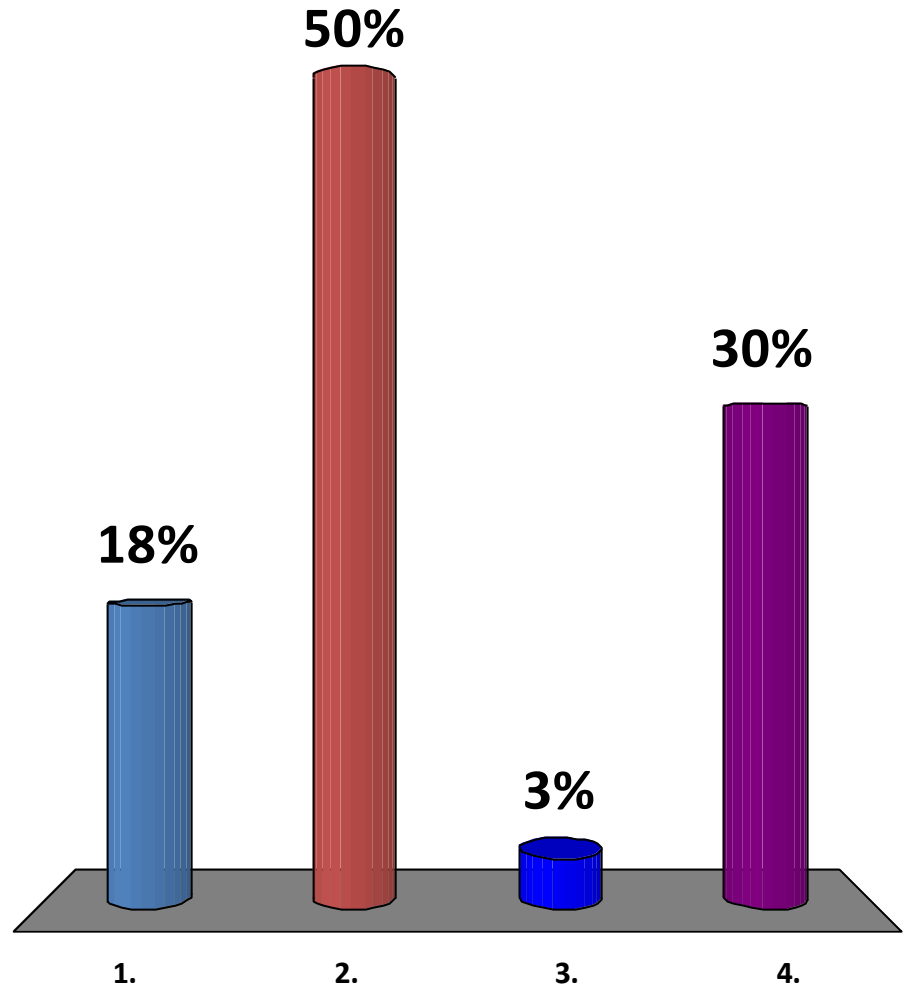
- Suppose a biomass concentration of 3.0 g/L is selected.
- Calculate θ_X , V , B_V , B_X , θ_H , ΔX , OD and E.

Exercise: general approach

- Make a drawing
- Fill in values
- What is missing? What do you need?
- Look at units
- Make a mass balance or use known formulas
- Solve the question

Calculate the volumetric loading rate

1. 0.97 kg/m³/d
- ✓ 2. 1.03 kg/m³/d
3. 0.32 kg/m³/d
4. ?



Equations

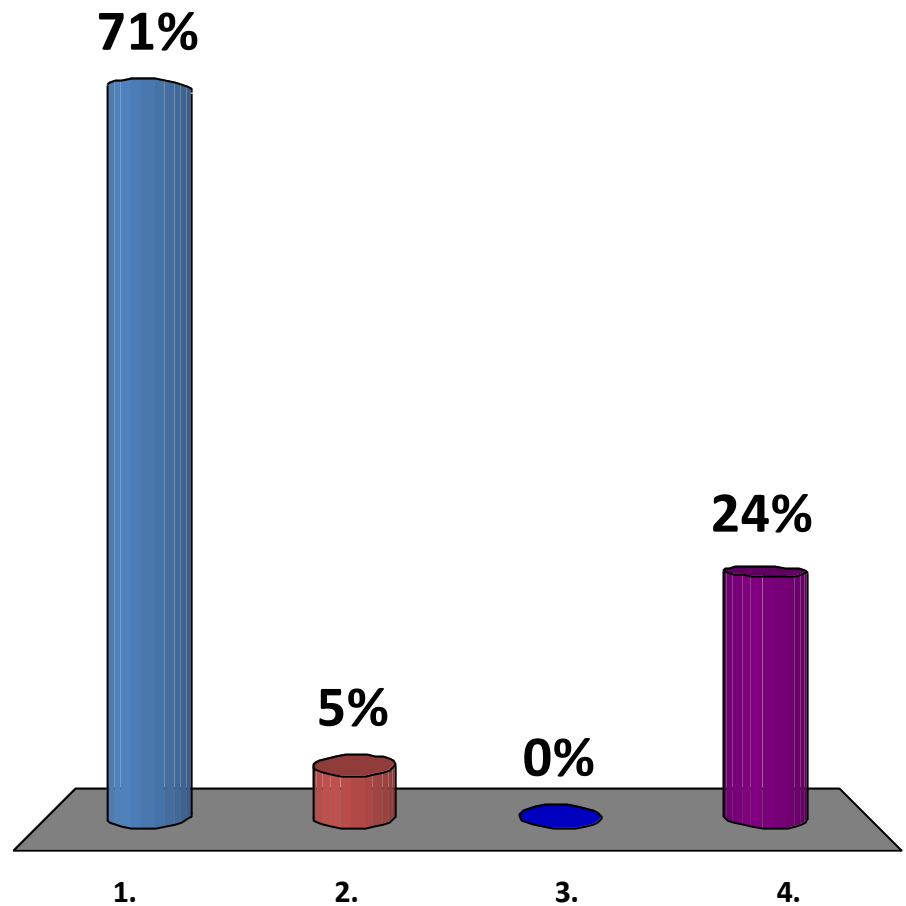
Characteristics	Completely mixed no recycle system	Completely mixed recycle system	Plug flow system
Waste removal efficiency	$E = \frac{100(S_0 - S)}{S_0}$	$E = \frac{100(S_0 - S)}{S_0}$	$E = \frac{100(S_0 - S_e)}{S_0}$
Effluent waste concentration (g/L)	$S = \frac{K_s(1 + b\theta_x)}{\theta_x(Y_{COD}^{max}q_{max} - b) - 1}$	$S = \frac{K_s(1 + b\theta_x)}{\theta_x(Y_{COD}^{max}q_{max} - b) - 1}$	No explicit solution for S_e
Biomass concentration in reactor (g/L)	$X = \frac{Y_{COD}^{max}(S_0 - S)}{1 + b\theta_x}$	$X = \frac{Y_{COD}^{max}(S_0 - S)}{(1 + b\theta_x)\bar{t}}$	$X = \frac{Y_{COD}^{max}(S_0 - S)\theta_x}{(1 + b\theta_x)\bar{t}}$
Excess biomass production rate (kg/d for Q in m^3/d ; S_0 and S_e in g/L)	$\Delta X = \frac{Y_{COD}^{max}Q(S_0 - S)}{1 + b\theta_x}$	$\Delta X = \frac{Y_{COD}^{max}Q(S_0 - S)}{1 + b\theta_x}$	$\Delta X = \frac{Y_{COD}^{max}Q(S_0 - S_e)}{1 + b\theta_x}$
Sludge growth rate (d^{-1})	$\mu = \frac{1}{\theta_x} = \frac{Y_{COD}^{max}q_{max}S}{K_s + S} - b$	$\mu = \frac{1}{\theta_x} = \frac{Y_{COD}^{max}q_{max}S}{K_s + S} - b$	$\mu = \frac{1}{\theta_x} = \frac{Y_{COD}^{max}q_{max}(S_0 - S_e)}{(S_0 - S_e) + (1 + R)K_s \ln(S_0/S_e)} - b$
			where $S_1 = \frac{S_0 + RS_e}{1 + R}$
Limiting or minimum biological solids retention time (d)	$\theta_x^{min} = \frac{1}{Y_{COD}^{max}q_{max} - b}$	$\theta_x^{min} = \frac{1}{Y_{COD}^{max}q_{max} - b}$	Not mathematically determined
Reactor volume (m^3)	$V = \frac{Y_{COD}^{max}Q\theta_x(S_0 - S)}{X(1 + b\theta_x)}$	$V = \frac{Y_{COD}^{max}Q\theta_x(S_0 - S)}{X(1 + b\theta_x)}$	$V = \frac{Y_{COD}^{max}Q\theta_x(S_0 - S)}{X(1 + b\theta_x)}$
Oxygen demand (kg/d)	$OD = Q(S_0 - S) - 1.33\Delta X$	$OD = Q(S_0 - S) - 1.33\Delta X$	$OD = Q(S_0 - S_e) - 1.33\Delta X$

Solution

- $\theta_x = \frac{1}{\frac{Y \cdot q_{max} \cdot S}{K_s + S} - b} = 7.77 \text{ d}$
- $V = \frac{Y_{COD}^{max} * Q * \theta_x (S_0 - S)}{X * (1 + b \theta_x)}$
 $= \frac{0.44 * (100 \text{ m}^3/\text{d} * 1000 \text{ L}/\text{m}^3) * 7.77 \text{ d} (1 \text{ g}/\text{L} - 0.015 \text{ g}/\text{L})}{3 \text{ g}/\text{L} * (1 + 0.02 \text{ d}^{-1} * 7.77 \text{ d})}$
 $= 97 \text{ 000 L}$
 $= 97 \text{ m}^3$
- $B_V = (100 \text{ m}^3/\text{d} * 1 \text{ kg}/\text{m}^3) / 97 \text{ m}^3$
 $= 1.03 \text{ kg}/\text{m}^3/\text{d}$
- $B_X = 1.03 \text{ kg} / \text{m}^3 / \text{d} / 3.0 \text{ kg} / \text{m}^3$
 $= 0.33 \text{ kg} / \text{kg VSS} / \text{d}$

Calculate the hydraulic residence time

- ✓ 1. 0.97 d
- 2. 1.03 d
- 3. 32 d
- 4. ?



Empirical design

- Volumetric loading, HRT, waste sludge, oxygen requirement,...
- Important: values p. 30: for balanced wastewaters:
 - 0,1 – 10 g bCOD/L
 - bCOD/N/P = 100/5/0,5
 - pH 6-8
 - T = 15 °C

Empirical design

Loading rate	Sludge loading $B_x = \text{kg bCOD/kg organic sludge} \cdot \text{d}$	Sludge age θ_x days	% BOD removal	Nitrification	Sludge			Oxygen requirement kg O ₂ /d
					SVI	Dewaterability	Surplus kg/d	
High	1.0 or more	1.0 or less	60 – 80	no	>100	poor	$0.4 \text{ bCOD} \times Q$	$0.6 \text{ bCOD} \times Q$
Conventional - without nitrification - with nitrification	0.5-1.0	5 to 10	90	no	>100	poor	$0.4 \text{ bCOD} \times Q$	$0.4 \text{ bCOD} \times Q$
	0.1-0.5	15 to 20	90	yes	75-150	fair	$0.4 \text{ bCOD} \times Q$	$(0.6 \text{ bCOD} + \text{NOD}) \times Q$
Low	Less than 0.1	More than 15	95	yes	mainly <100	good	$0.2 \text{ bCOD} \times Q$	$(0.8 \text{ bCOD} + \text{NOD}) \times Q$

Sludge treatment

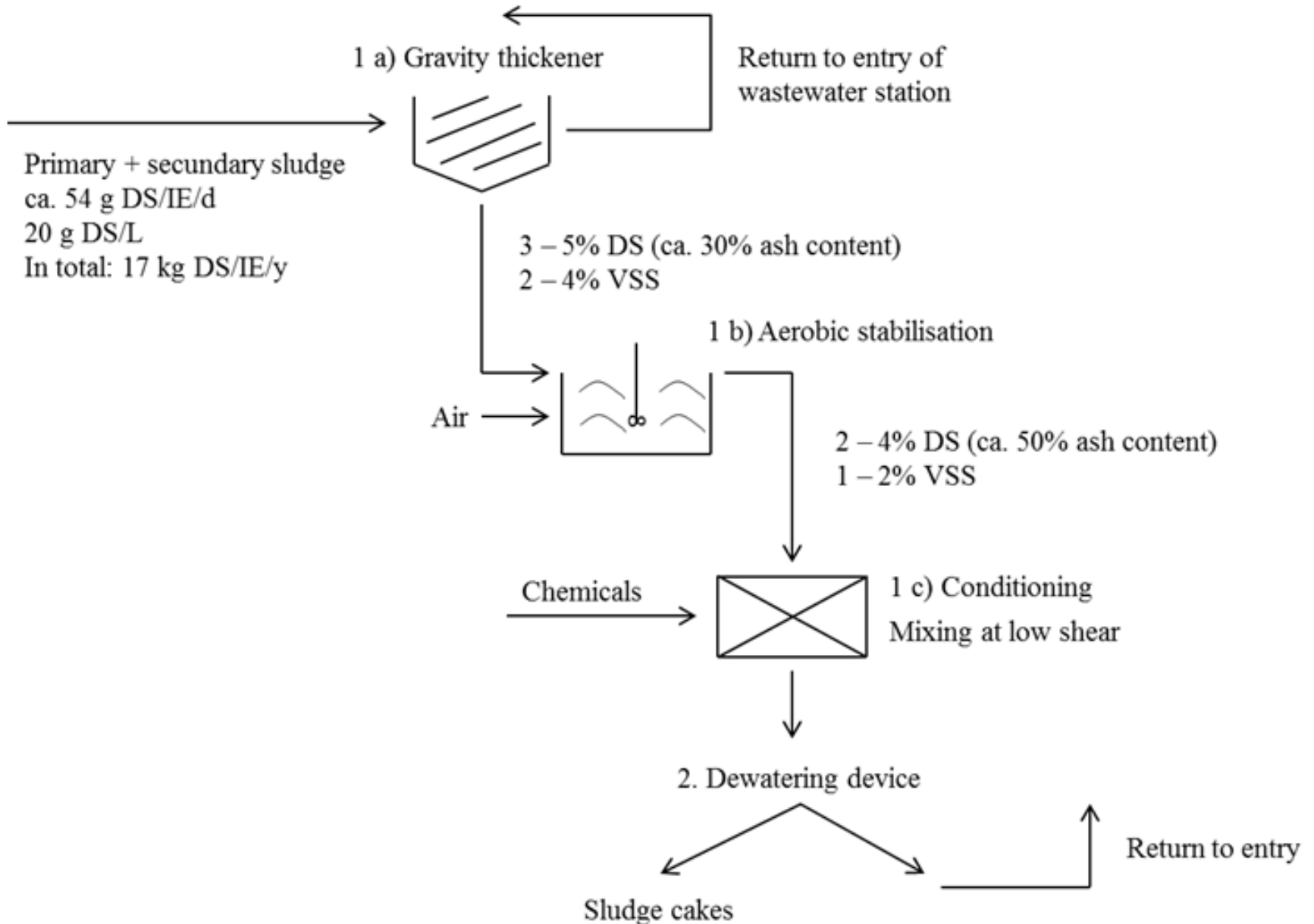
- Per IE: 54 – 60 g DS/IE d
- Costs: 625 euro/ton DS treated (after incineration + landfill)
- 14 euro/IE.y
- Waste sludge: 1-2 % DS (10-20 g/L)
 - Thickening/Stabilisation/Conditioning (-> 3-5 % DS)
 - Dewatering: chemically + physically (25-45 % DS)

Main purpose; transport solids, not water!

Legislation

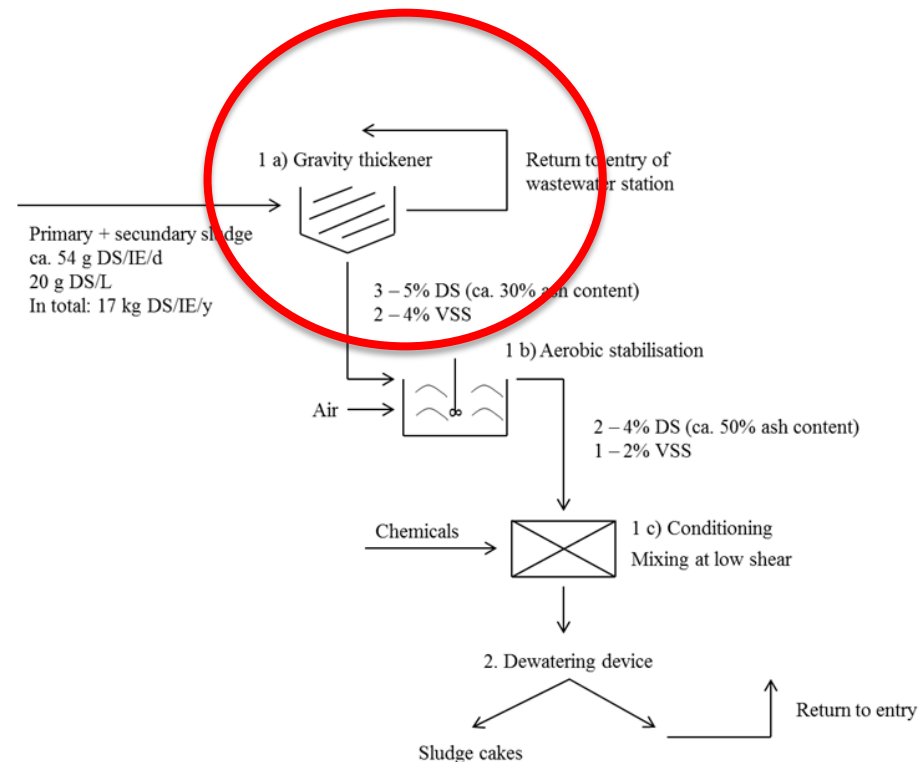
- Sludge can be applied as a fertilizer
- Strong legislations
 - Heavy metals
 - PCBs, PAHs, dioxins
 - Different types based on pathogen content
 - Class A: extensive treatment
 - Class B: partial treatment
 - Need of certification

Aerobic stabilization



Process design

- Gravity thickener: 2 kg DS/m²/h loading rate
- Aerobic stabilization
 - HRT, SRT = 10-20 d
 - Loading rate = 1,5 – 4,5 kg VSS/m³/d
 - DO 1-2 mg/L
 - 60% removable VSS

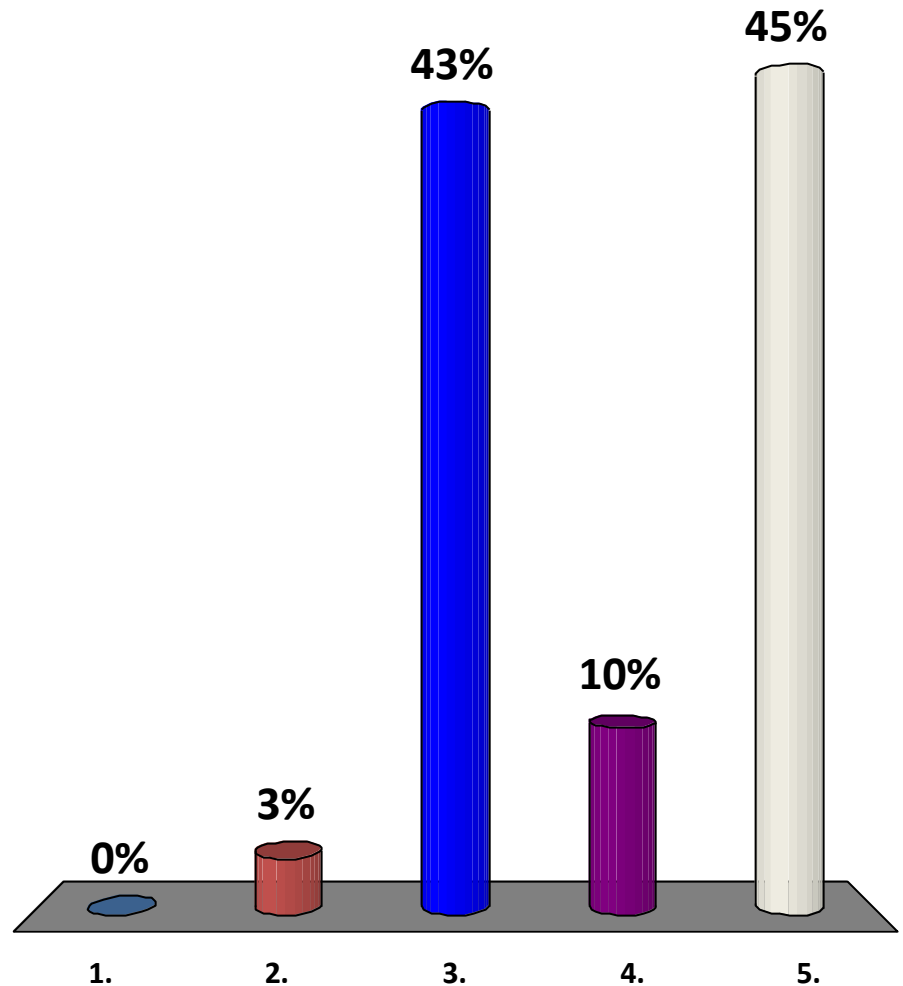


Exercise 1 p. 36

- 40 000 IE; 50 g DS/IE/d
- Concentration: 1,5 % → 3% in gravity thickener, loading at 48 kg/m²/d, depth of 4m (default)
- Aerobic stabilization
 - 20 d
 - 67 m³/d
 - 50% VSS oxidized by air
 - VSS/TSS = 0,7 (TSS = DS)
 - 1 kg VSS → 1,33 kg COD
 - Supply: 2X what is needed (OC/load =2)
 - 2 kg O₂/kWh

Volume of the thickener?

1. 384 m³
2. 11 m³
- ✓ 3. 168 m³
4. 42 m³
5. ?



Solution

- Kg waste sludge/d :

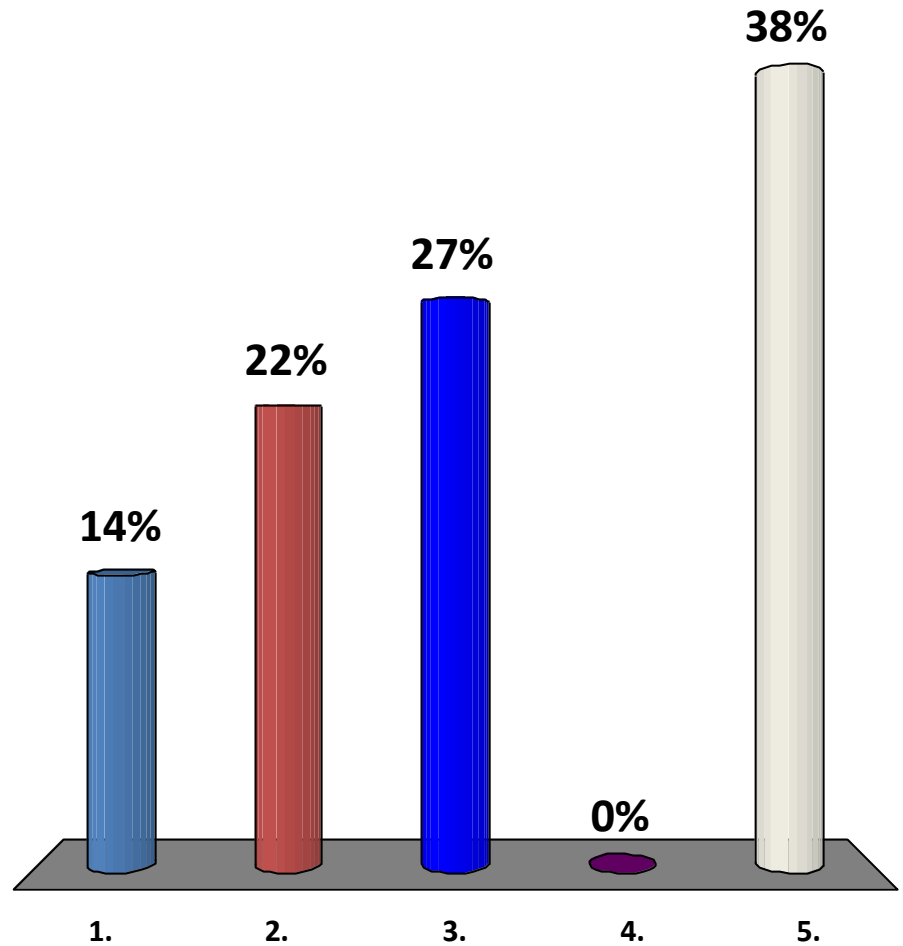
$$40\ 000\ \text{IE} \times (50\ \text{g DS/IE/d}) \times 10^{-3} \\ = 2000\ \text{kg DS/d.}$$

- surface : $\frac{2000\ \text{kg/d}}{48\ \text{kg/m}^2 \cdot \text{d}} = 42\ \text{m}^2$

-volume : $42\ \text{m}^2 \times 4\ \text{m} \\ = 168\ \text{m}^3$

Calculate the residence time in the thickener

- ✓ 1. 1,26 d
- 2. 2,52 d
- 3. 12,6 d
- 4. 25,2 d
- 5. ?

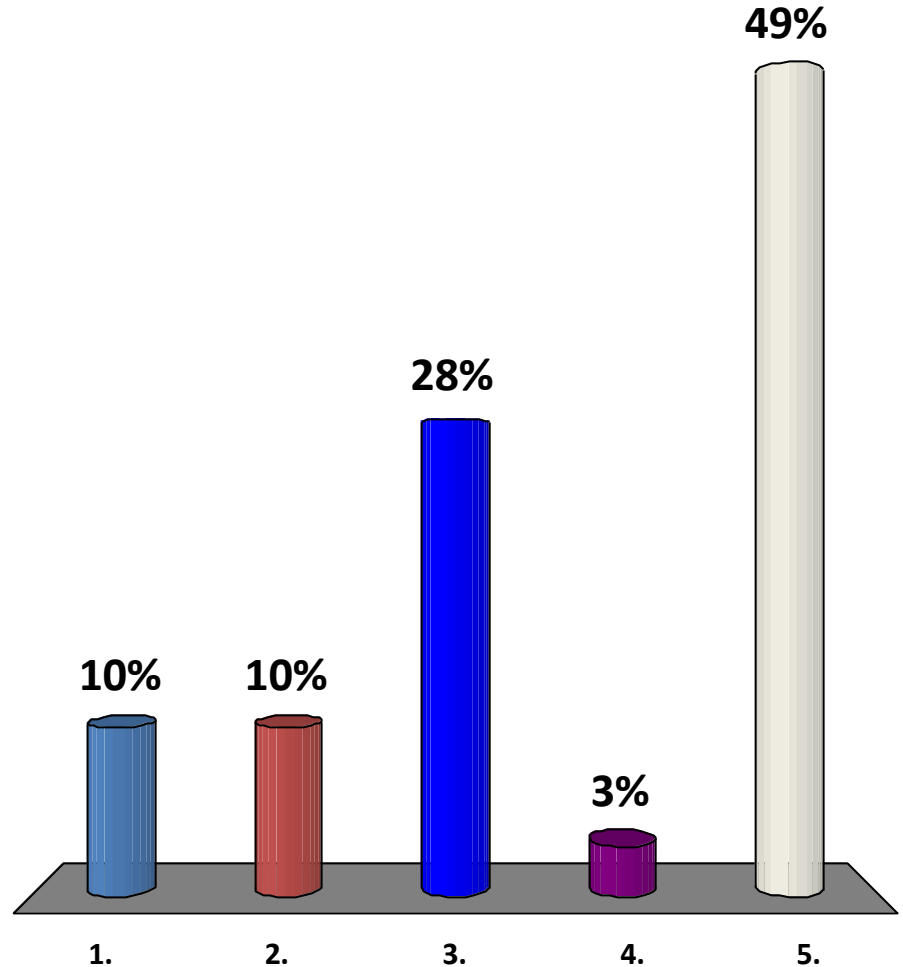


- Flow rate = $\frac{2000 \text{ kg DS} / d}{15 \text{ kg} / m^3} = 133 m^3 / d$

- Residence time = $\frac{168 m^3}{133 m^3 / d} = 1.26 d$

Calculate the volume of air needed per day

1. 1862 m³/d
2. 3103 m³/d
- ✓ 3. 6207 m³/d
4. 8867 m³/d
5. ?



- Volume of the aerobic digestion basin = $67 \text{ m}^3 / \text{d}$ of thickened sludge $\times 20 \text{ d} \approx 1300 \text{ m}^3$

$$\begin{aligned}
 \text{Kg O}_2 \text{ required} &= 2000 \text{ kg Total Suspended Solids (TSS=DS)}/\text{d} \\
 &\times 0.7 \text{ (fraction of VSS/TSS)} \\
 &\times 1.33 \text{ (1 kg VSS} \approx \text{1.33 kg COD)} \\
 &\times 0.5 \text{ (fraction of sludge oxidised)} \\
 &\times 2 \text{ (OC/load : one supplies 2 x the amount strictly} \\
 &\text{needed by stoichiometry)}
 \end{aligned}$$

$$= 1862 \text{ kg O}_2/\text{d}$$

- Volume of air required (ideal gas law: $1 \text{ mol} = 22.4 \text{ L}$; 21% O_2 in air)

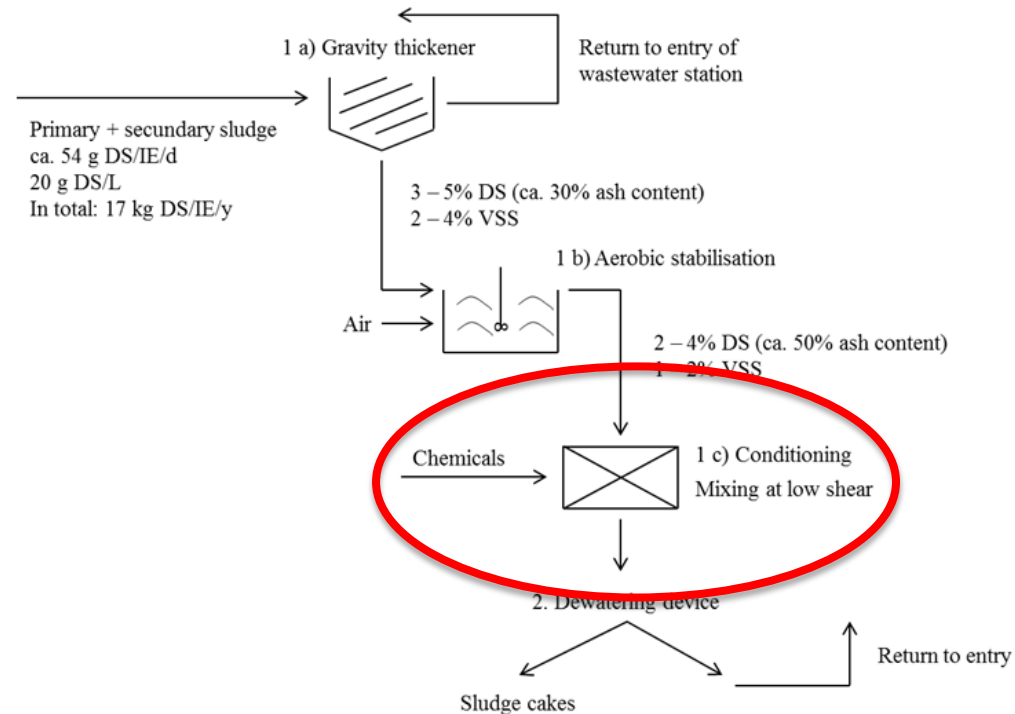
$$\frac{[(1862 \text{ kg O}_2/\text{d}) / (32 \text{ kg O}_2 / \text{kmol})] * 22,4 \text{ m}^3/\text{kmol}}{0,21} = \mathbf{6207 \text{ m}^3/\text{d}}$$

Power input

- Power input (assume 2.0 kg O₂/kWh) =
1862 kg O₂ / (2 kg O₂ / kWh) = 931 kWh/d

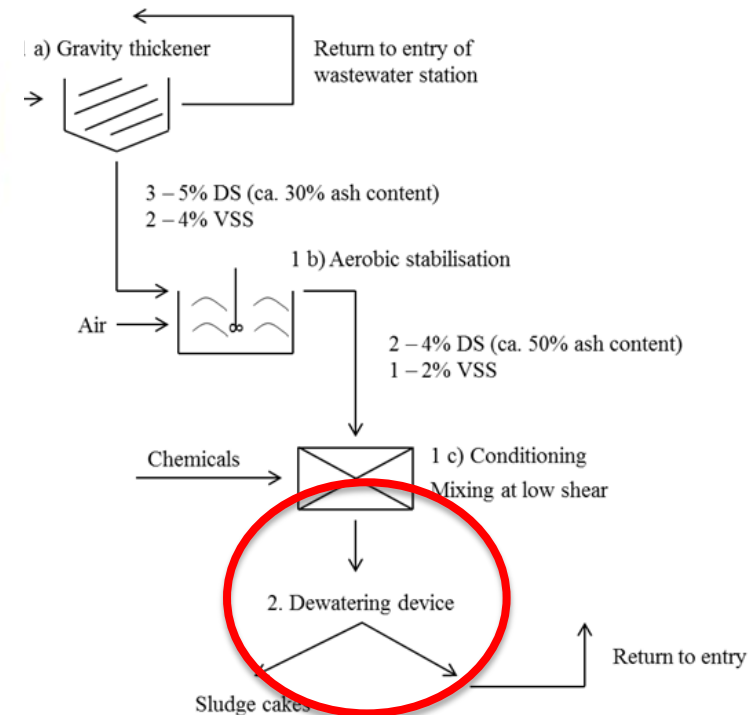
Conditioning chemicals

- Coagulants/flocculants to stabilize and precipitate colloidal particles
- FeCl_3 , $\text{Ca}(\text{OH})_2$, polyacrylamide
- Polymers: preferred above metals



Mechanical dewatering devices

- Filter press

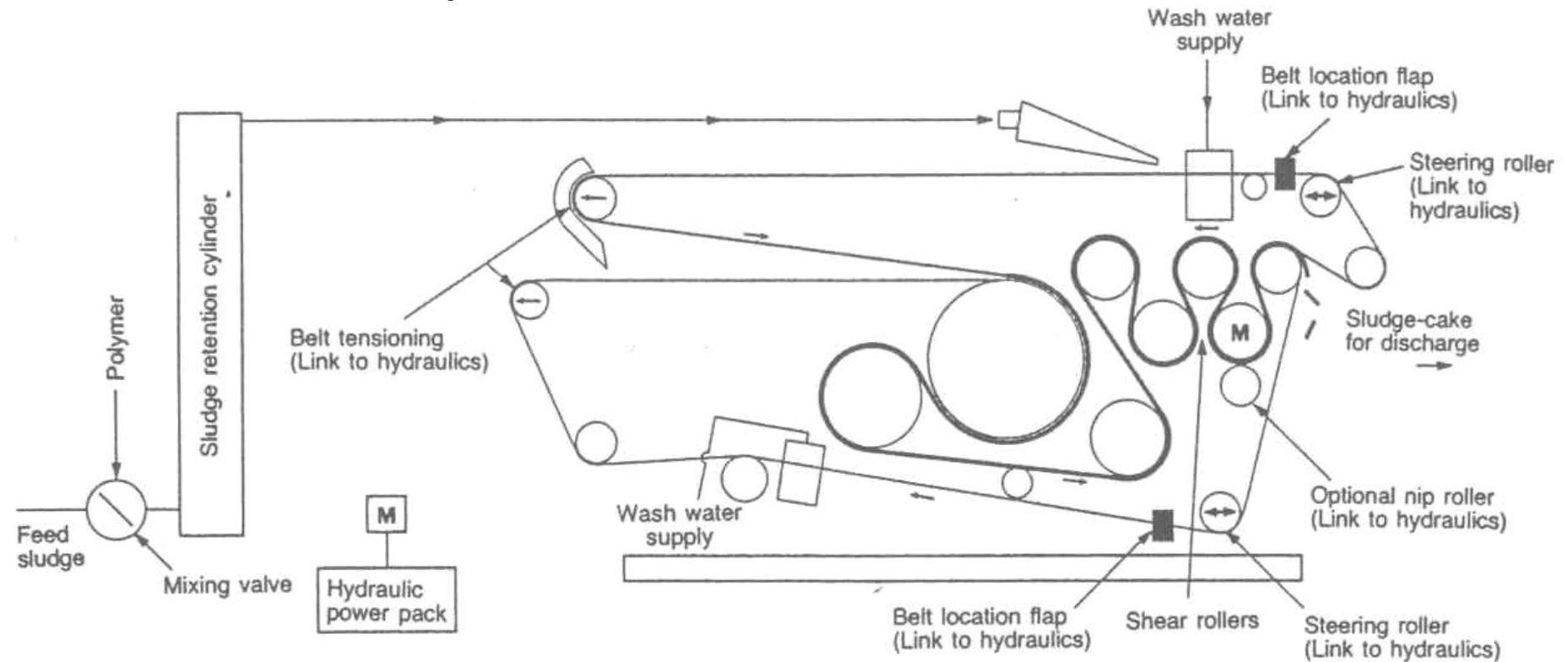


https://www.youtube.com/watch?v=M4wBd1_CvNw



Mechanical dewatering devices

- Belt filter press

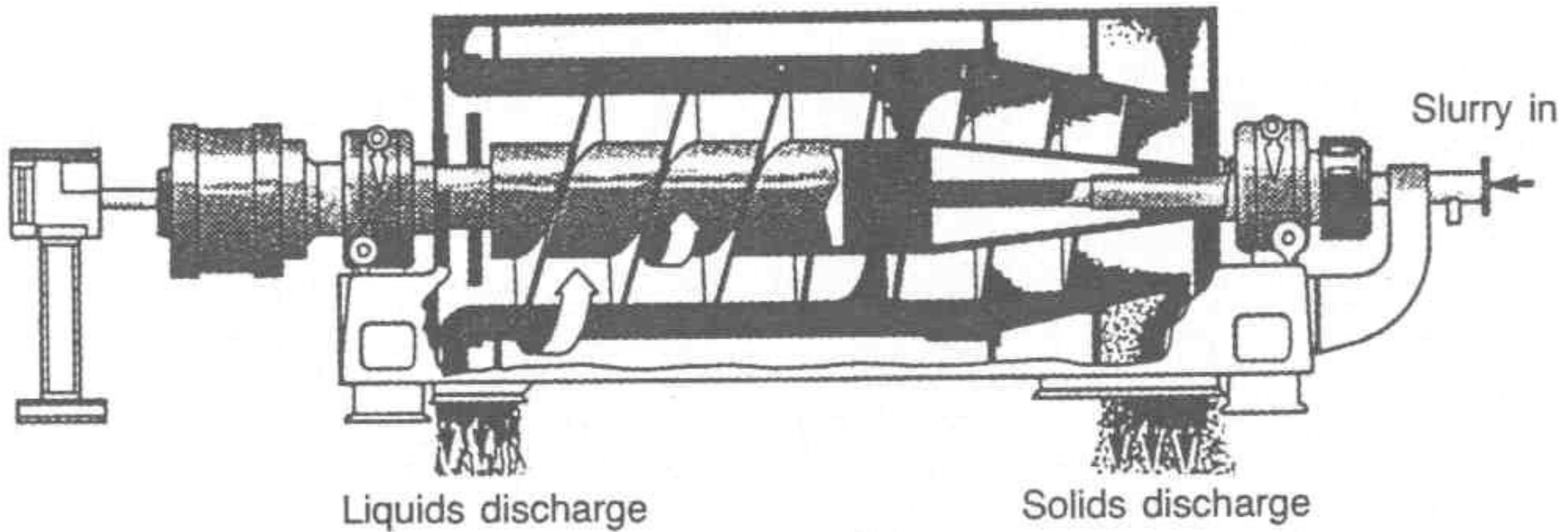


M = motor

<https://www.youtube.com/watch?v=iQAxVqCL2rk>

Mechanical dewatering devices

- Centrifuge



<https://www.youtube.com/watch?v=dJvaLB0AZjA>

Alternative techniques

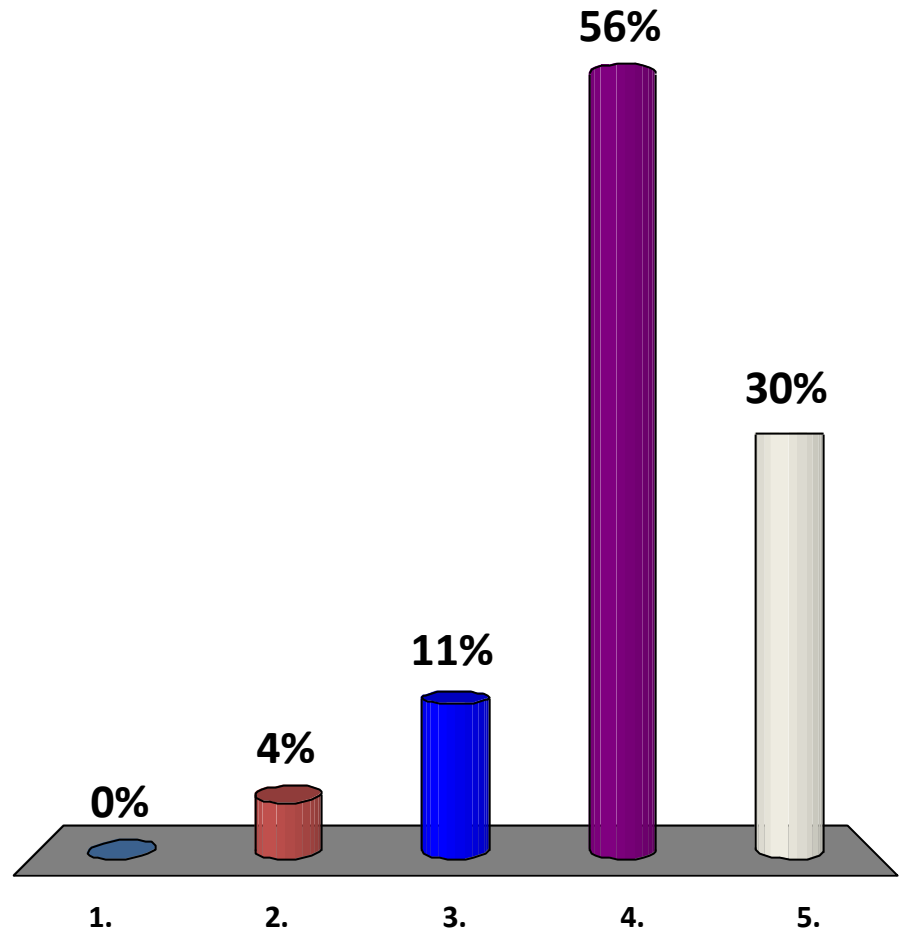
- Oxidation
 - Use of air: wet oxidation: air under pressure at high temperature
 - Ozonation: under ambient pressure and temperature, but costly
- Anaerobic digestion
 - In absence of oxygen
 - Production of biogas:
1 kg COD \rightarrow 0,5 m³ biogas \rightarrow 1 kWh

Exercise 2

- Sludge: 1200 kg DM/d, 3% DM, 35 % degradable
- 1 kg DM = 1,3 kg COD
- Inside T = 34°C, outside T = 10°C
- 36,7 MJ/m³
- Specific heat: 4200 J/(kg.°C)
- Transfer through the wall= 0,60 W/(m².°C)
- Height = 12m
- 0,35 m³ methane/kg COD digested

Calculate the volume of the digester

1. 0.72 m^3
2. 0.80 m^3
3. 720 m^3
- ✓ 4. 800 m^3
5. ?



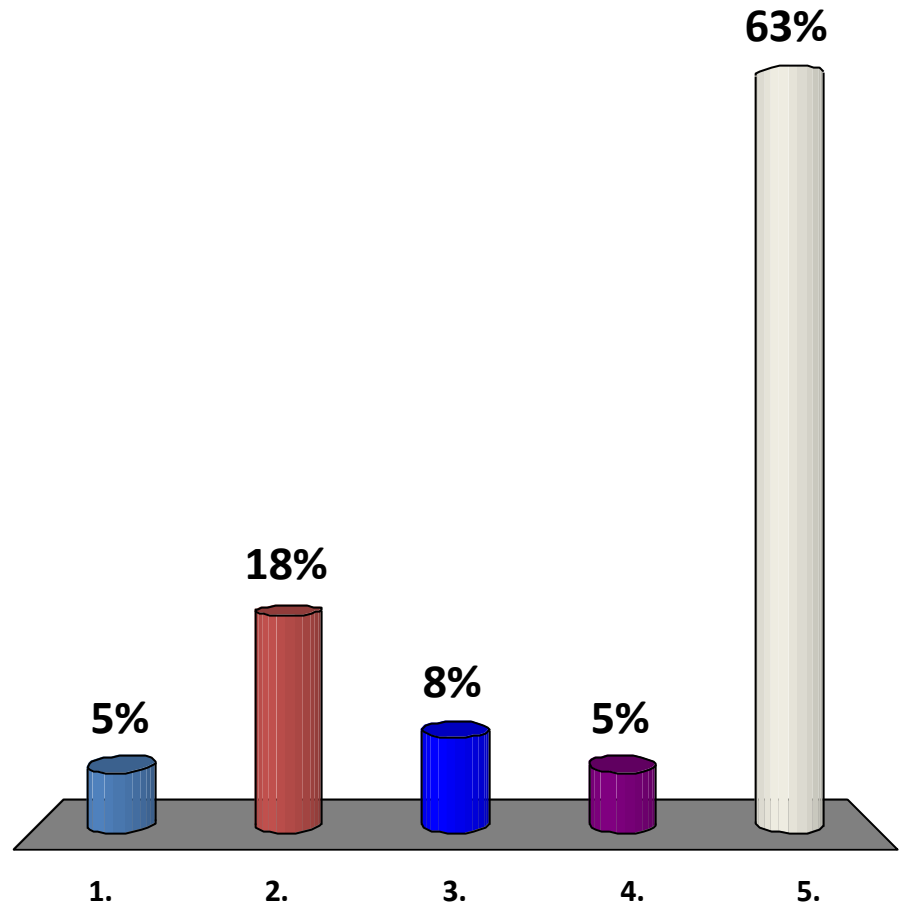
Volume anaerobic digester

$$Q_{in} = \frac{1200 \text{ kg DM/d}}{30 \text{ kg DM/m}^3}$$
$$= 40 \text{ m}^3/\text{d}$$

$$V = 40 \text{ m}^3/\text{d} * 20\text{d}$$
$$= 800 \text{ m}^3$$

Calculate the heath requirements

1. 4032 MJ/d
- ✓ 2. 4629 MJ/d
3. 597 MJ/d
4. 3435 MJ/d
5. ?



- $V = \pi * r^2 * h \rightarrow \text{diameter} = 2r = 9,21 \text{ m}$
- Heat requirements: sludge DM and water

Sludge: $\frac{1200 \text{ kg DM/d}}{30 \text{ kg DM/m}^3} = 40 \text{ m}^3/\text{d}$

* 1000 kg/m^3

* $(34 \text{ }^\circ\text{C} - 10 \text{ }^\circ\text{C})$

* $4200 \text{ J}/(\text{kg}\cdot^\circ\text{C})$

= 4032 MJ/d

- Losses:

– Surface of the digester = $2 * \pi * 4,6^2 + 2 * 4,6 * \pi * 12 = 480 \text{ m}^2$

– Heat loss = $0.60\text{W}/\text{m}^2\cdot^\circ\text{C} * 480 \text{ m}^2 * (34^\circ\text{C}-10^\circ\text{C}) * 3600 \text{ s/h} * 24 \text{ h/d}$

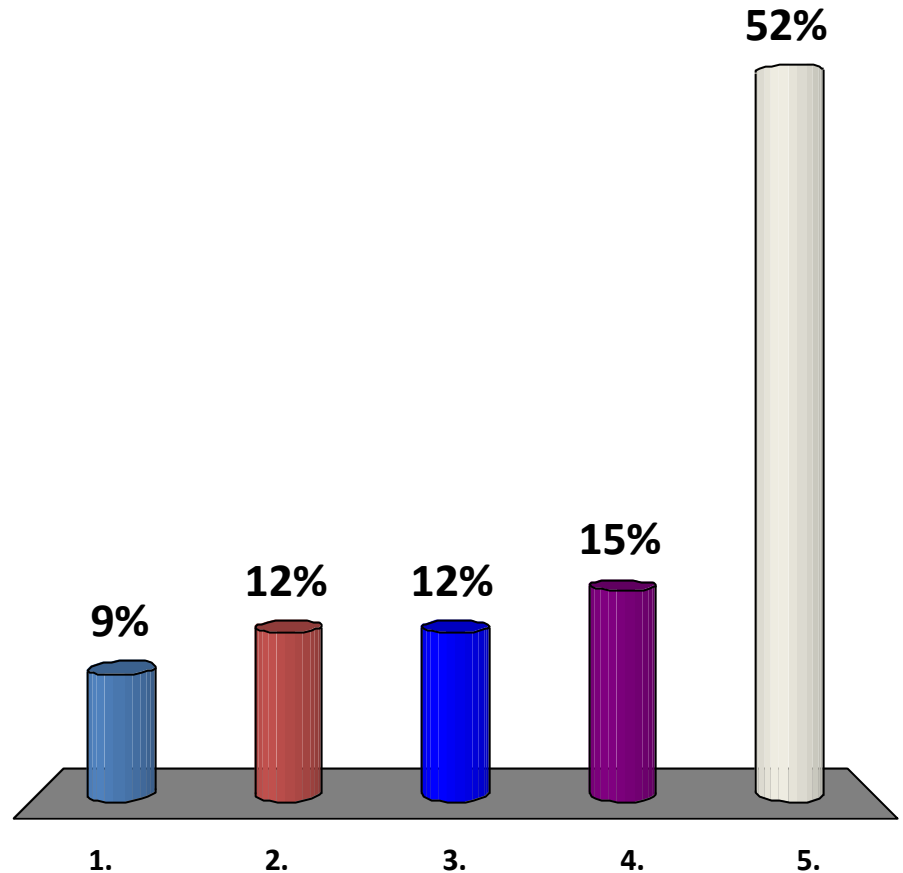
= 597 MJ/d

- Total heat requirements = $4032 \text{ MJ/d} + 597 \text{ MJ/d}$

= **4629 MJ/d**

Energy production?

- ✓ 1. 1948 kWh/d
- 2. 7013 kWh/d
- 3. 20038 kWh/d
- 4. 25247 kWh/d
- 5. ?



$$\text{COD}_{\text{in}} = 1560 \text{ kgCOD/d}$$

COD degraded

$$= 1560 \text{ kgCOD/d} * 0.35$$

$$= 546 \text{ kgCOD/d}$$

Methane production

$$= 0,35 * 546$$

$$= 191.1 \text{ m}^3 \text{ CH}_4/\text{d}$$

Total energy production

$$= 191.1 \text{ m}^3 \text{ CH}_4/\text{d} * 36.7 \text{ MJ/m}^3$$

$$= 7013 \text{ MJ/d}$$

$$= 1948 \text{ kWh/d}$$

Wrap-up

At the end of the semester you can:

- Make a schematic drawing of a WWTP
- Set-up and solve a mass-balance of a WWTP or its unit processes
- Calculate operational parameters based on biokinetic values
- Estimate operational costs/gain of a WWTP