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
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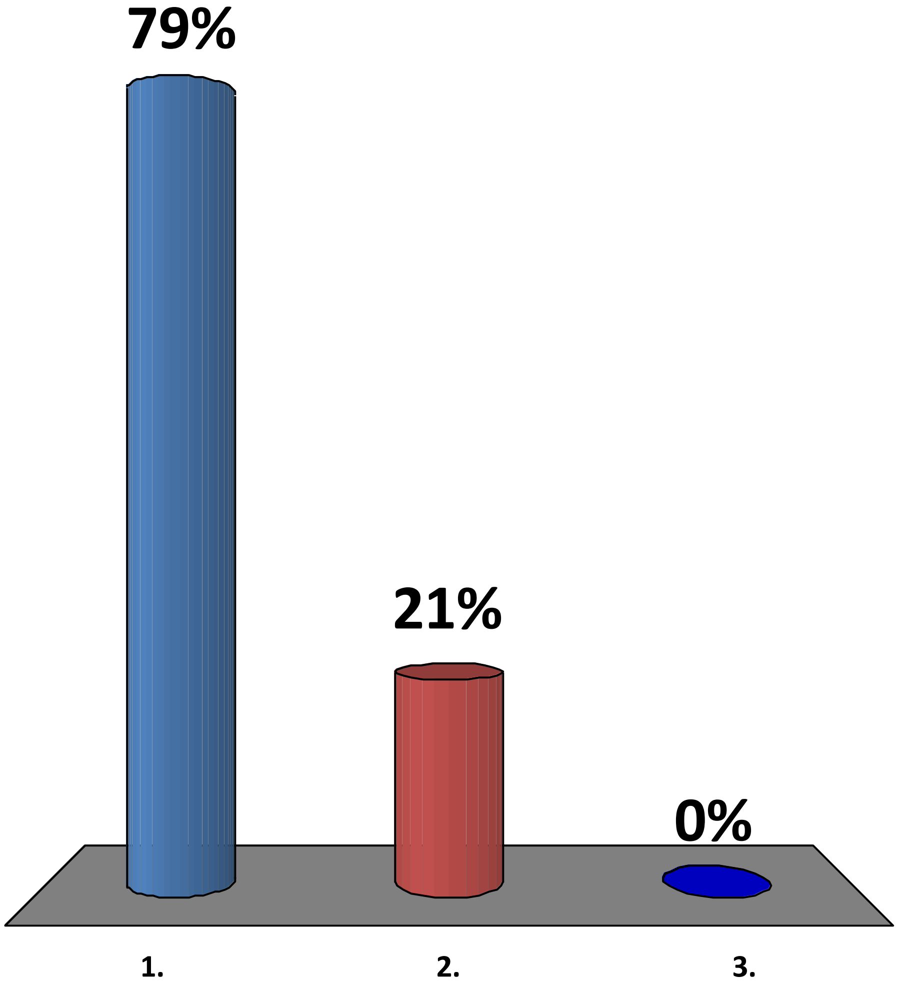
4/11/2015

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 it’s unit processes
- Calculate operational parameters based on biokinetic values
- Estimate operational costs/gain of a WWTP

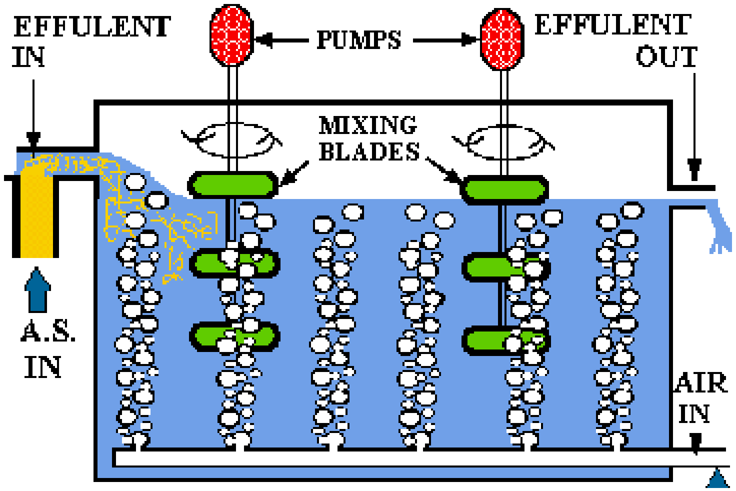
Biokinetic values

- Microbial community: biokinetic constants
  - Y^{max} : yield (g VSS/g substrate)
  - b : decay coefficient
  - q_{max} : maximum growth rate
  - K_s : substrate affinity coefficient

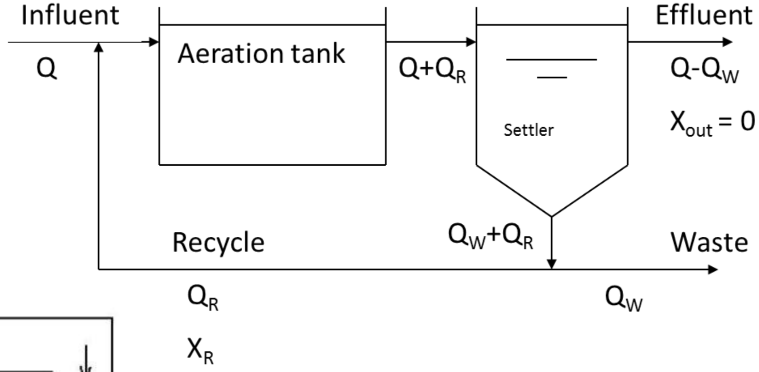
- Determined by lab scale reactors and pilot plants

3 types

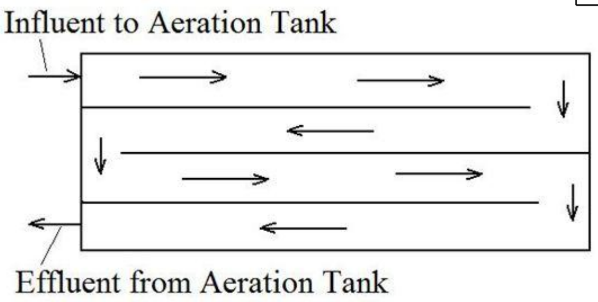
- Completely mixed, no recycle



- Completely mixed, recycle



- Plug flow



Serpentine Pattern, 'Plug Flow
Activated Sludge Aeration Tank

Equations

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 m³/d; S_o 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})	$\mu = \frac{1}{\theta_X} = \frac{Y_{COD}^{max} q_{max} S}{K_S + S} - b$	$\mu = \frac{1}{\theta_X} = \frac{Y_{COD}^{max} q_{max} S}{K_S + S} - b$	$\mu = \frac{1}{\theta_X} = \frac{Y_{COD}^{max} q_{max}(S_0 - S_e)}{(S_0 - S_e) + (1 + R)K_S \ln(S_i / S_e)} - b$ where $S_i = \frac{S_0 + RS_e}{1 + R}$
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 (m³)	$V = \frac{Y_{COD}^{max} Q\theta_X(S_0 - S)}{X(1 + b\theta_X)}$	$V = \frac{Y_{COD}^{max} Q\theta_X(S_0 - S)}{X(1 + b\theta_X)}$	$V = \frac{Y_{COD}^{max} Q\theta_X(S_0 - S)}{X(1 + b\theta_X)}$
Oxygen demand (kg/d)	$OD = Q(S_0 - S) - 1.33\Delta X$	$OD = Q(S_0 - S) - 1.33\Delta X$	$OD = Q(S_0 - S_e) - 1.33\Delta X$

Exercise P.28

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

Operational:

- Q = 100 m^3/d
- S_0 = bCOD = 1.0 g/L
- $S_{effluent}$ = 15 mg bCOD/L (10 mg BOD_5/L).

Biological:

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

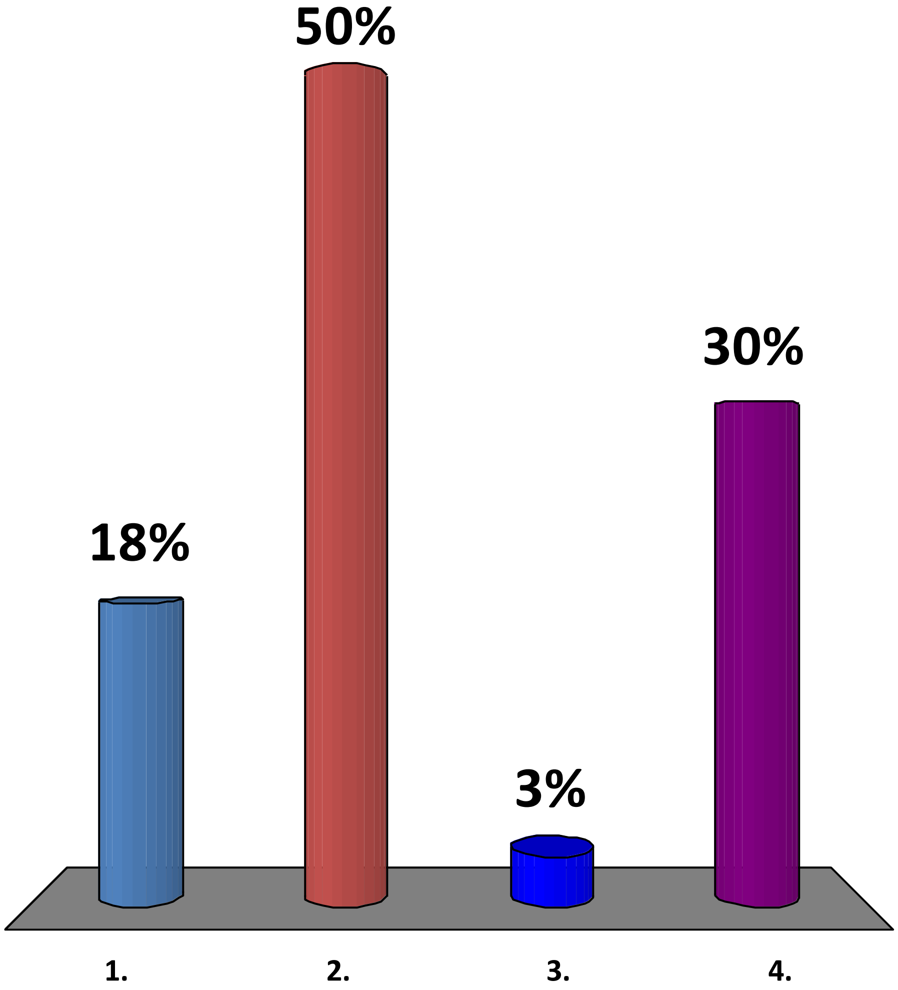
- Suppose a biomass concentration of 3.0 g/L is selected.
- Calculate θ_X, V, B_V, $B_{X,}$ θ_H, ΔX, OD and E.

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 $kg/m^3/d$
2. [✓ 1.03 $kg/m^3/d$]
3. 0.32 $kg/m^3/d$
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 m³/d; S₀ and Sₑ 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)	$\mu = \frac{1}{\theta_X} = \frac{Y_{COD}^{\max} q_{\max} S}{K_S + S} - b$	$\mu = \frac{1}{\theta_X} = \frac{Y_{COD}^{\max} q_{\max} S}{K_S + S} - b$	$\mu = \frac{1}{\theta_X} = \frac{Y_{COD}^{\max} q_{\max}(S_0 - S_e)}{(S_0 - S_e) + (1 + R)K_S \ln(S_i / S_e)} - b$ where $S_i = \frac{S_0 + RS_e}{1 + R}$
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Reactor volume (m³)	$V = \frac{Y_{COD}^{\max} Q\theta_X(S_0 - S)}{X(1 + b\theta_X)}$	$V = \frac{Y_{COD}^{\max} Q\theta_X(S_0 - S)}{X(1 + b\theta_X)}$	$V = \frac{Y_{COD}^{\max} Q\theta_X(S_0 - S)}{X(1 + b\theta_X)}$
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

- $\theta_x = \frac{1}{\frac{Y.q_{max}.S}{K_S + S} - b} = 7.77\ d$

- $V = Y_{COD}^{max} * Q * \theta_X (S_0 – S) / (X * (1 + b\ \theta_X))$

  $$= \frac{0.44 * (100\ m3/d * 1000\ L/m3) * 7.77\ d\ (1\ g/L - 0.015\ g/L)}{3\ g/L * (1 + 0.02\ d - 1 * 7.77\ d)}$$

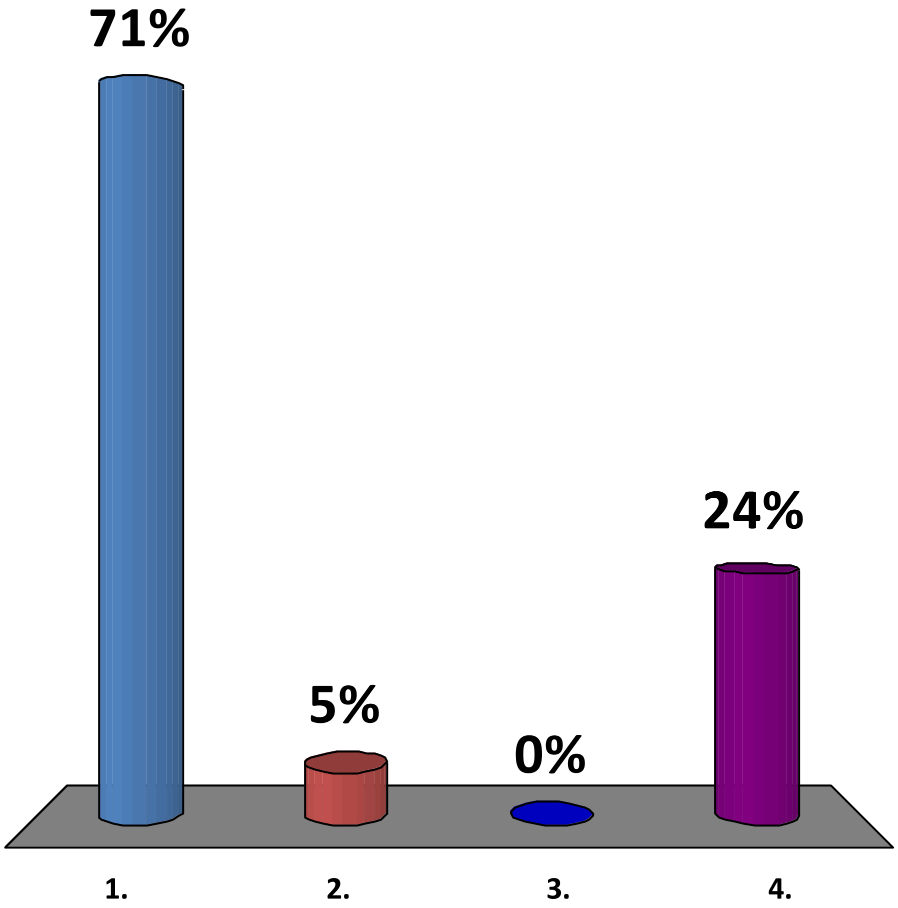
  = 97 000 L
  = 97 m^3

- B_V = (100 m^3/d * 1 kg/m^3)/97 m^3
  = 1.03 kg/m^3/d

- B_X = 1.03 kg / m^3 / d / 3.0 kg / m^3
  = 0.33 kg / kg VSS / d

Calculate the hydraulic residence time

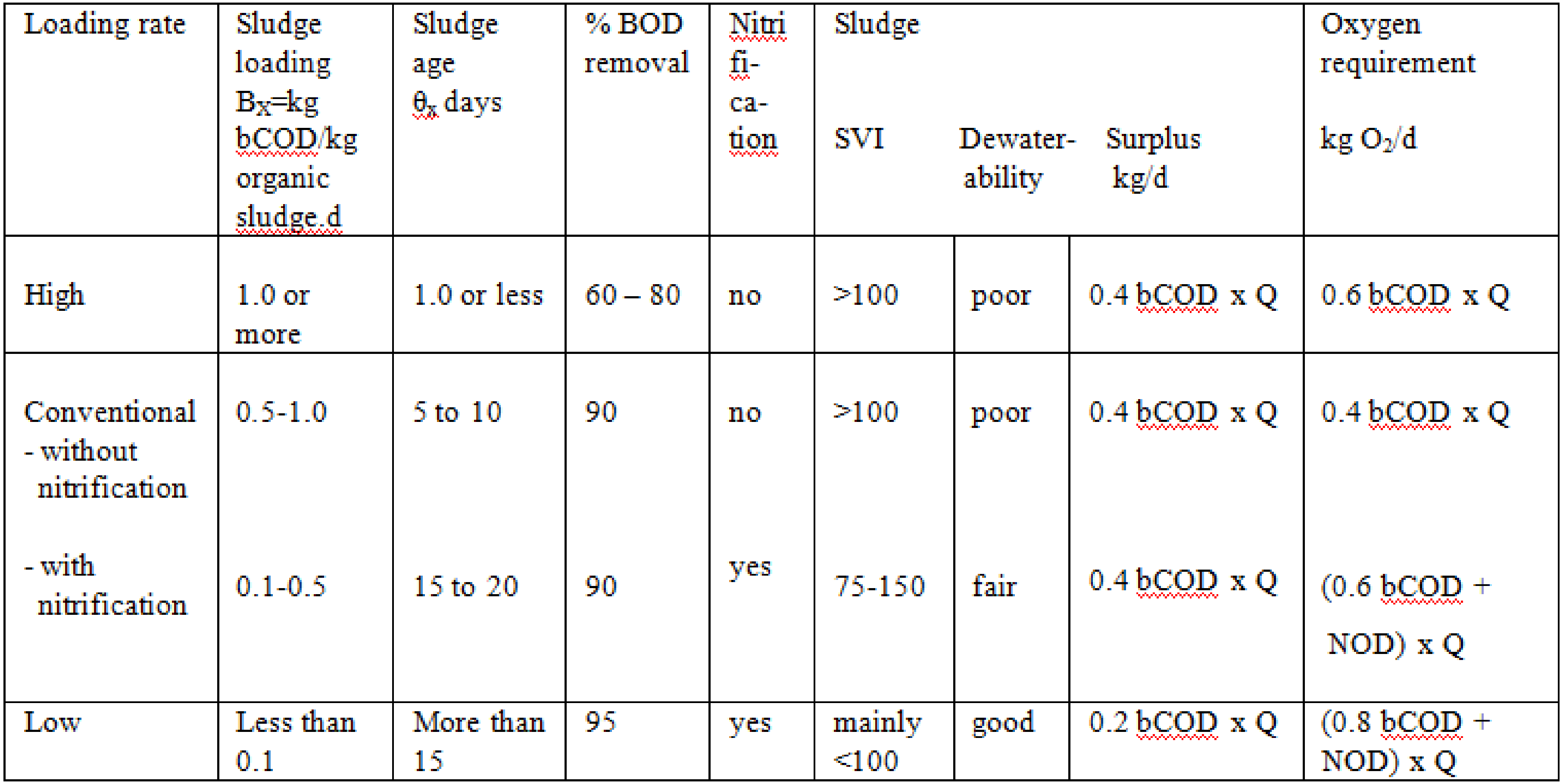
1. ✓ 0.97 d
2. 1.03 d
3. 32 d
4. ?



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=kg bCOD/kg organic sludge.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 bCOD x Q	0.6 bCOD x Q
Conventional - without nitrification	0.5-1.0	5 to 10	90	no	>100	poor	0.4 bCOD x Q	0.4 bCOD x Q
- with nitrification	0.1-0.5	15 to 20	90	yes	75-150	fair	0.4 bCOD x Q	(0.6 bCOD + NOD) x Q
Low	Less than 0.1	More than 15	95	yes	mainly <100	good	0.2 bCOD x Q	(0.8 bCOD + NOD) x Q

Sludge treatment

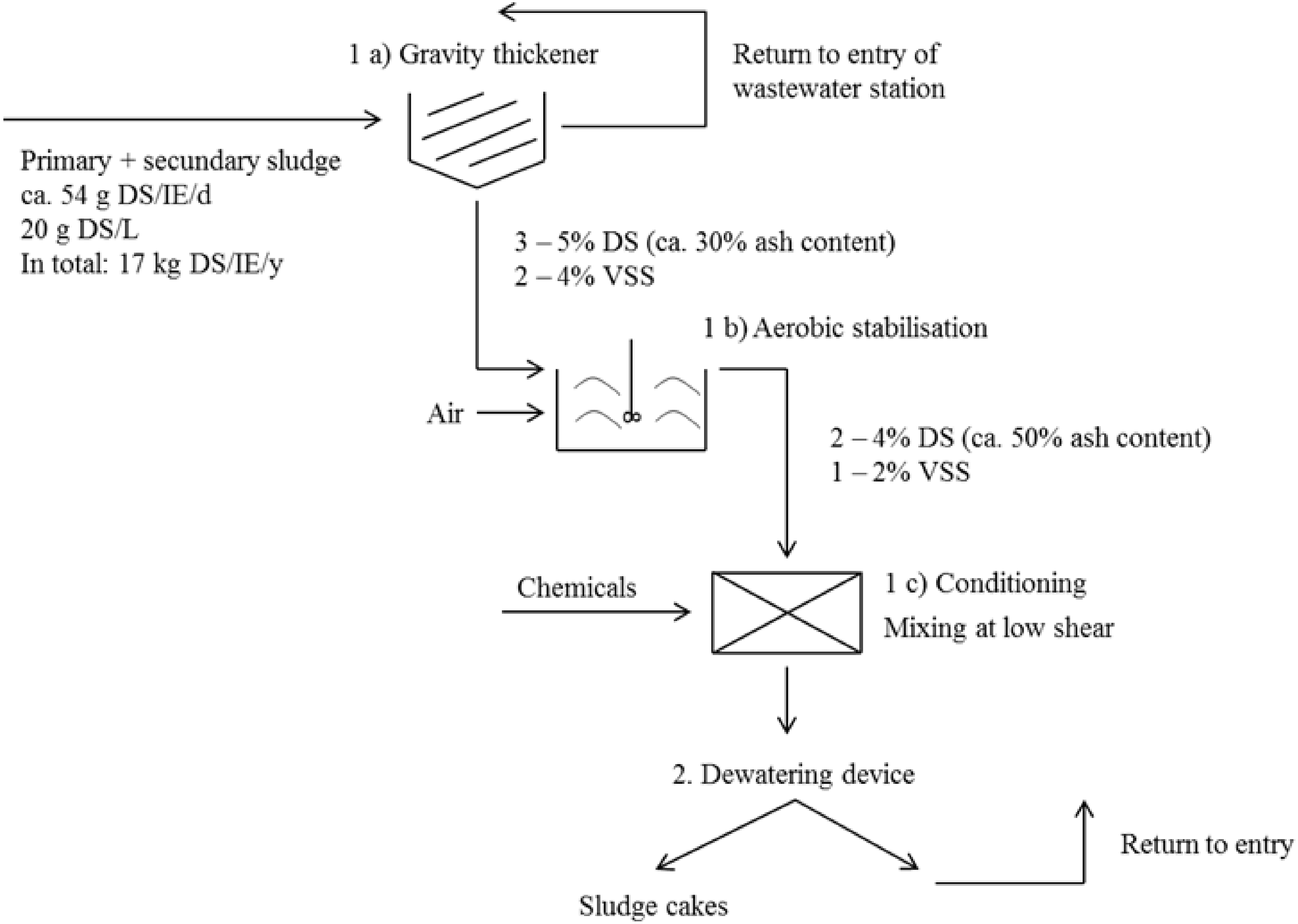
- Per IE: 54 – 60 g DS/IE d
- Costs: 625 euro/ton DS treated (after incineration + landfill)
- 14 euro/IE.y
- Waste sludge:1-2 % DS (10-20 g/L)
  - Thickening/Stablisation/Conditioning (-> 3-5 % DS)
  - Dewatering: chemically + physically (25-45 % DS)

Main purpose; transport solids, not water!

Legislation

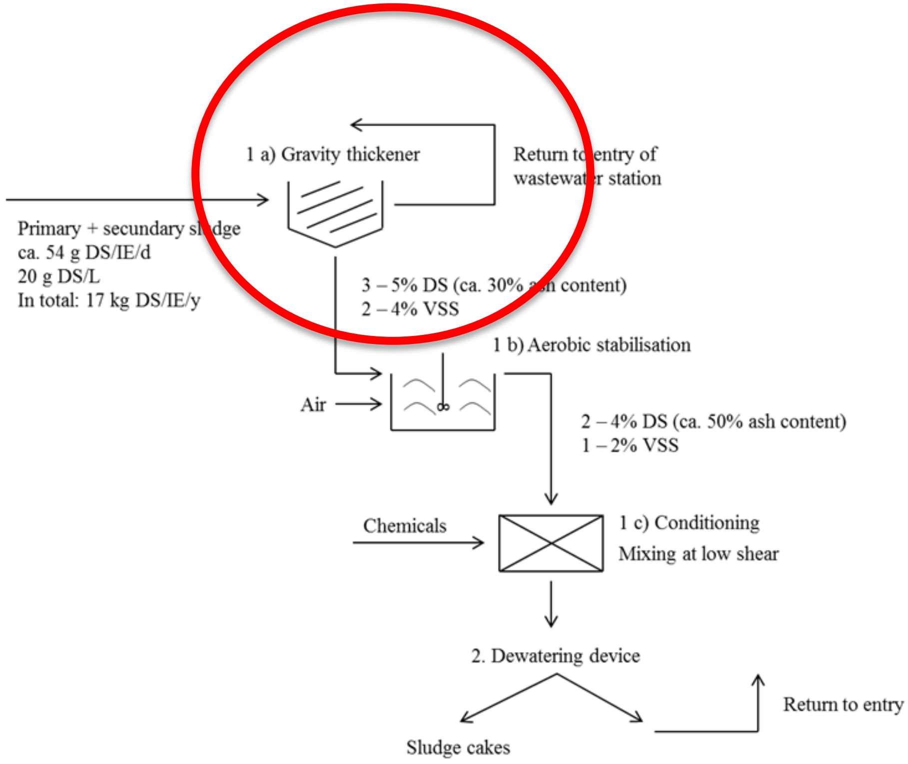
- Sludge can be applied as a fertilizer
- Strong legislations
  - Heavy metals
  - PCBs, PAHs, dioxins
  - Different types based on pathogen content
    - Class A: extensive treatment
    - Class B: partial treatment
  - Need of certification

Aerobic stabilization



Process design

- Gravity thickener: 2 kg DS/m^2/h loading rate
- Aerobic stabilization
  - HRT, SRT = 10-20 d
  - Loading rate = 1,5 – 4,5 kg VSS/m^3/d
  - DO 1-2 mg/L
  - 60% removable VSS

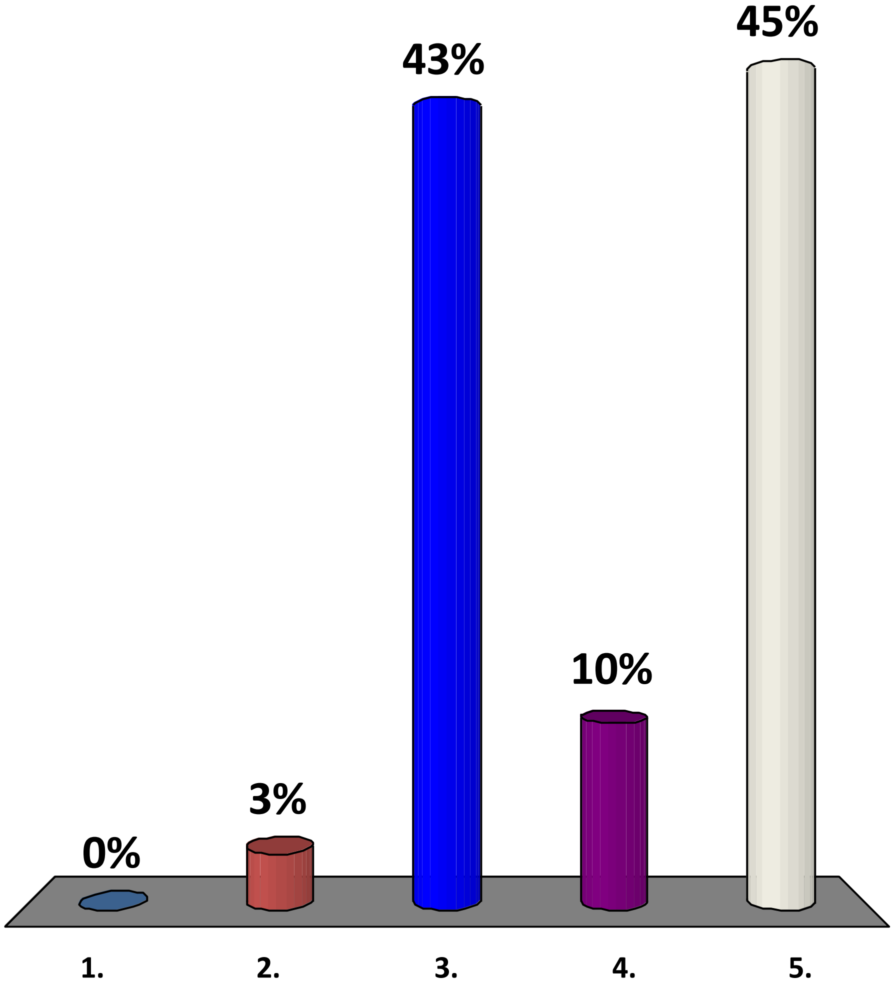


Exercise 1 p. 36

- 40 000 IE; 50 g DS/IE/d
- Concentration: 1,5 % → 3% in gravity thickener, loading at 48 kg/m^2/d, depth of 4m (default)
- Aerobic stabilization
  - 20 d
  - 67 m^3/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 O_2/kWh

Volume of the thickener?

1. 384 m^3
2. 11 m^3
3. ✓ 168 m^3
4. 42 m^3
5. ?



Solution

- Kg waste sludge/d :

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

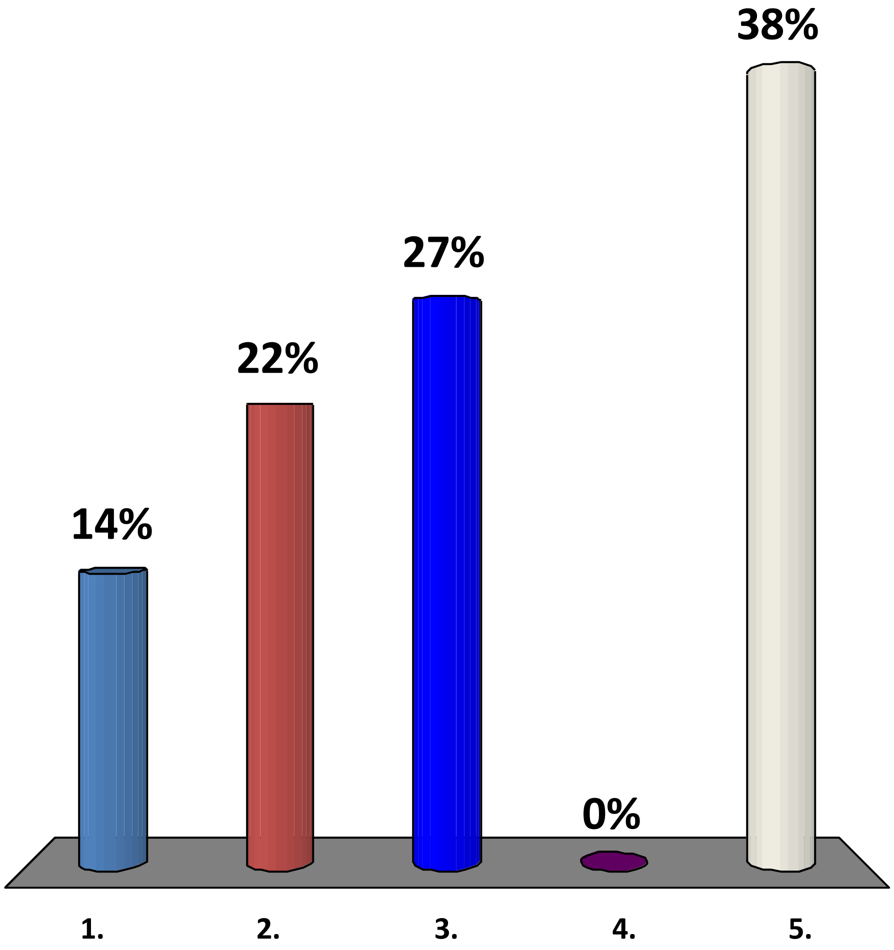
- surface : $\frac{2000\,\mathrm{kg/d}}{48\,\mathrm{kg/m^2.d}} = 42\ \mathrm{m}^2$

-volume : 42 m^2 x 4 m

= 168 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. ?

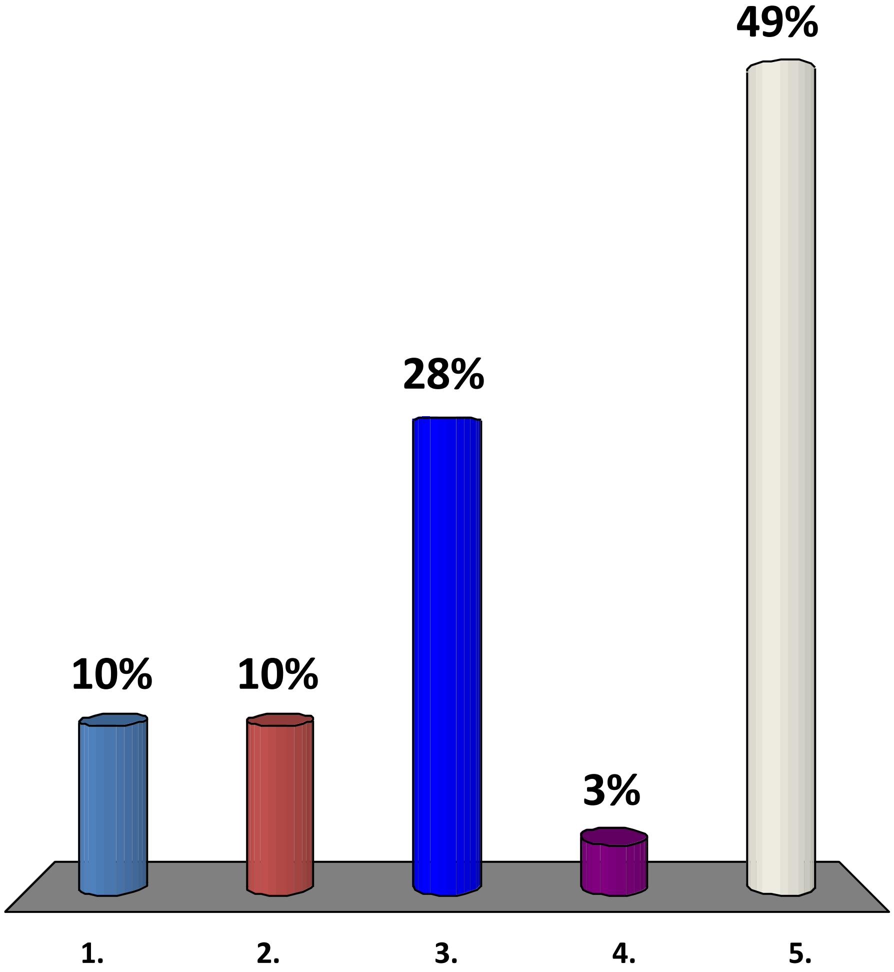


- Flow rate = $\dfrac{2000\,kg\,DS/d}{15\,kg/m^3} = 133\,m^3/d$

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

Calculate the volume of air needed per day

1. 1862 m^3/d
2. 3103 m^3/d
3. [✓ 6207 m^3/d]
4. 8867 m^3/d
5. ?



- Volume of the aerobic digestion basin = 67 m^3 /d of thickened sludge x 20 d ≈ 1300 m^3

Kg O_2 required = 2000 kg Total Suspended Solids (TSS=DS)/d
x 0.7 (fraction of VSS/TSS)
x 1.33 (1 kg VSS ≈ 1.33 kg COD)
x 0.5 (fraction of sludge oxidised)
x 2 (OC/load : one supplies 2 x the amount strictly needed by stoichiometry)

= 1862 kg O_2/d

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

$$\frac{[(1862 \text{ kg } O_2/\text{d})/(32 \text{ kg } O_2 /\text{kmol})]*22{,}4 \text{ m}^3/\text{kmol}}{0{,}21} = \mathbf{6207\ m^3/d}$$

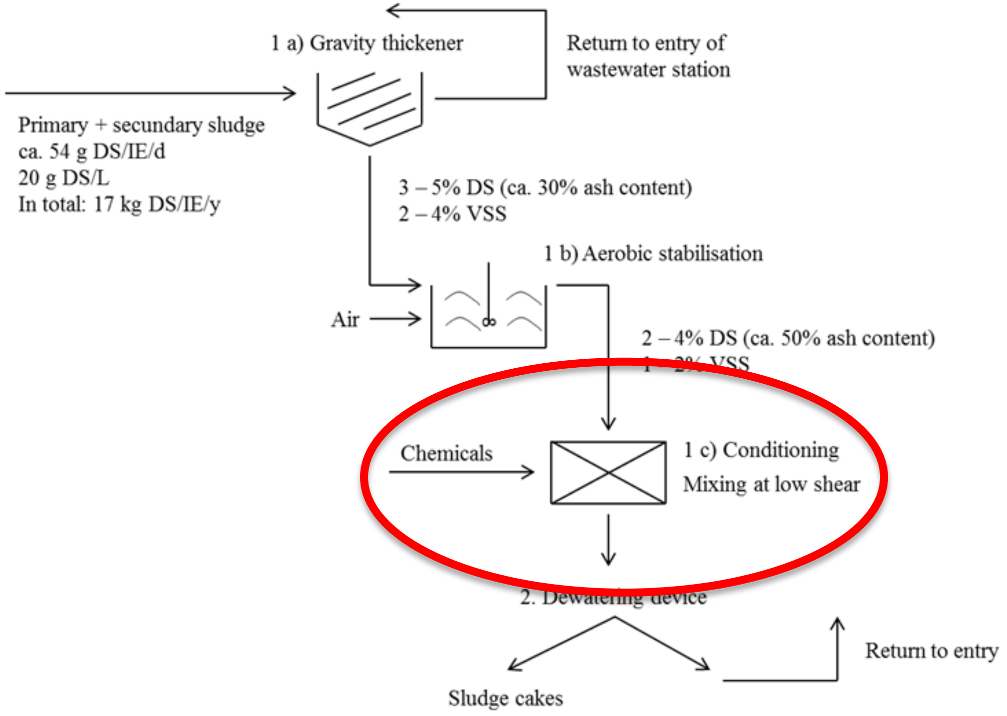
Power input

- Power input (assume 2.0 kg O_2/kWh) =

  1862 kg O_2 / (2 kg O_2 / kWh) = 931 kWh/d

Conditioning chemicals

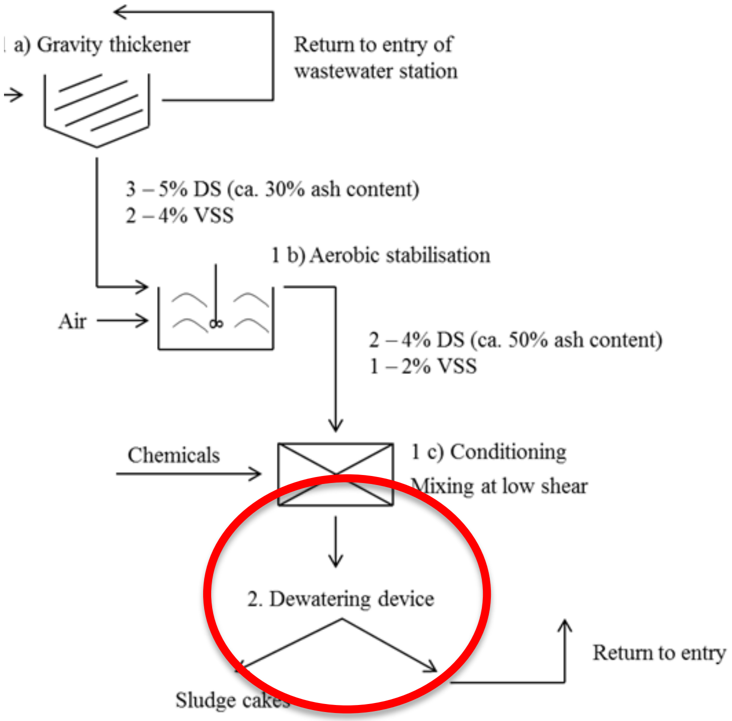
- Coagulants/flocculants to stabilize and precipitate colloidal particles
- $FeCl_3$, $Ca(OH)_2$, polyacrylamide
- Polymers: preferred above metals



Mechanical dewatering devices

- Filter press

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



a) Gravity thickener

Return to entry of
wastewater station

3 – 5% DS (ca. 30% ash content)
2 – 4% VSS

1 b) Aerobic stabilisation

Air

2 – 4% DS (ca. 50% ash content)
1 – 2% VSS

Chemicals

1 c) Conditioning
Mixing at low shear

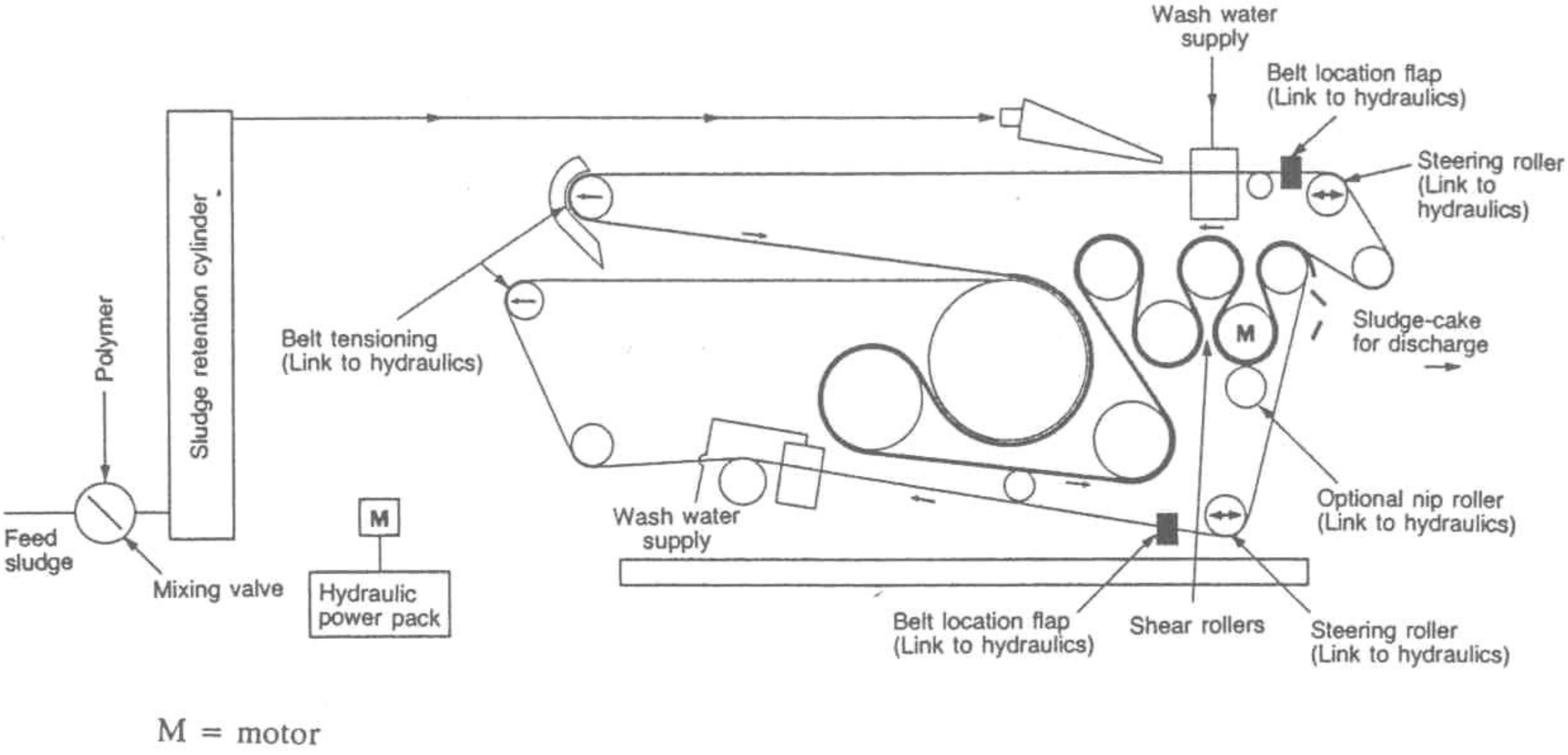
2. Dewatering device

Sludge cakes

Return to entry

Mechanical dewatering devices

- Belt filter press



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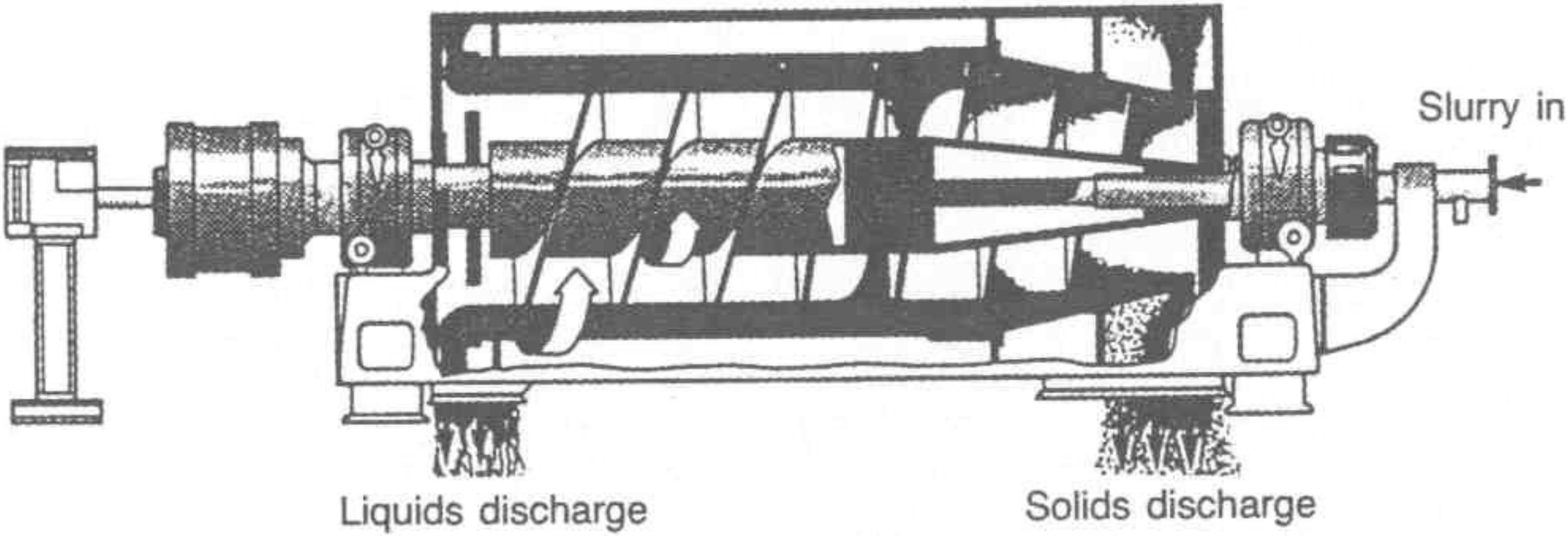
Mechanical dewatering devices

- 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:

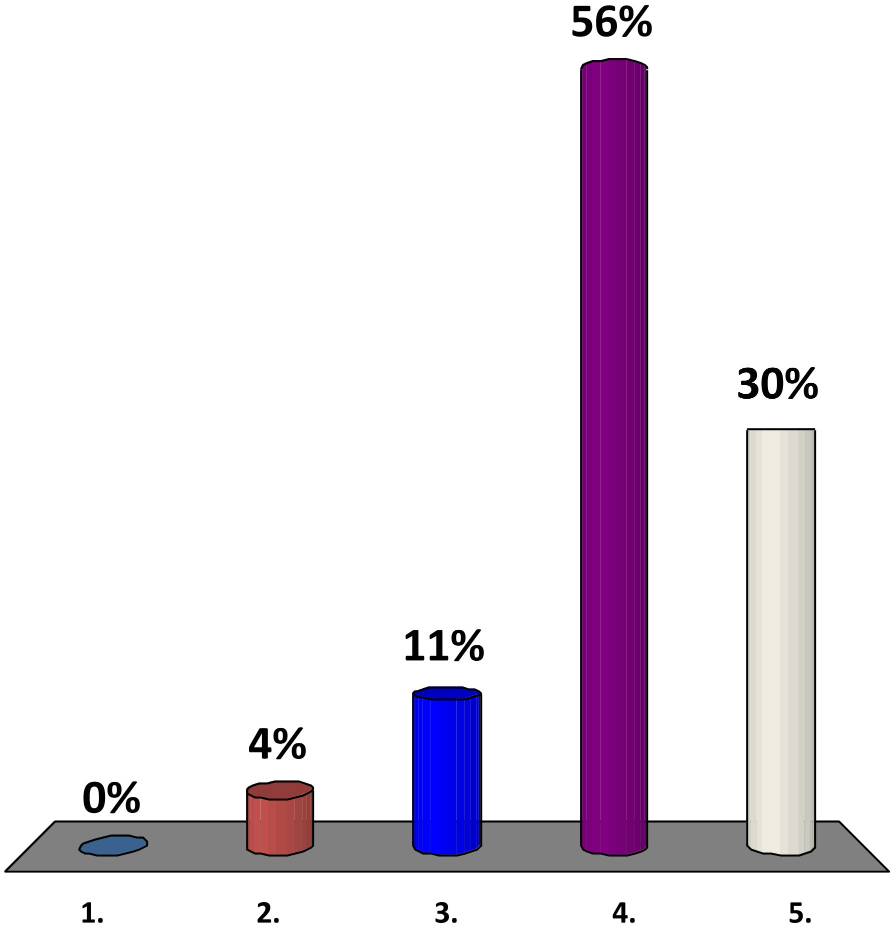
    1 kg COD → 0,5 m^3 biogas → 1 kWh

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/m^3
- Specific heat: 4200 J/(kg.°C)
- Transfer through the wall= 0,60 $W/(m^2.°C)$
- Height = 12m
- 0,35 m^3 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

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

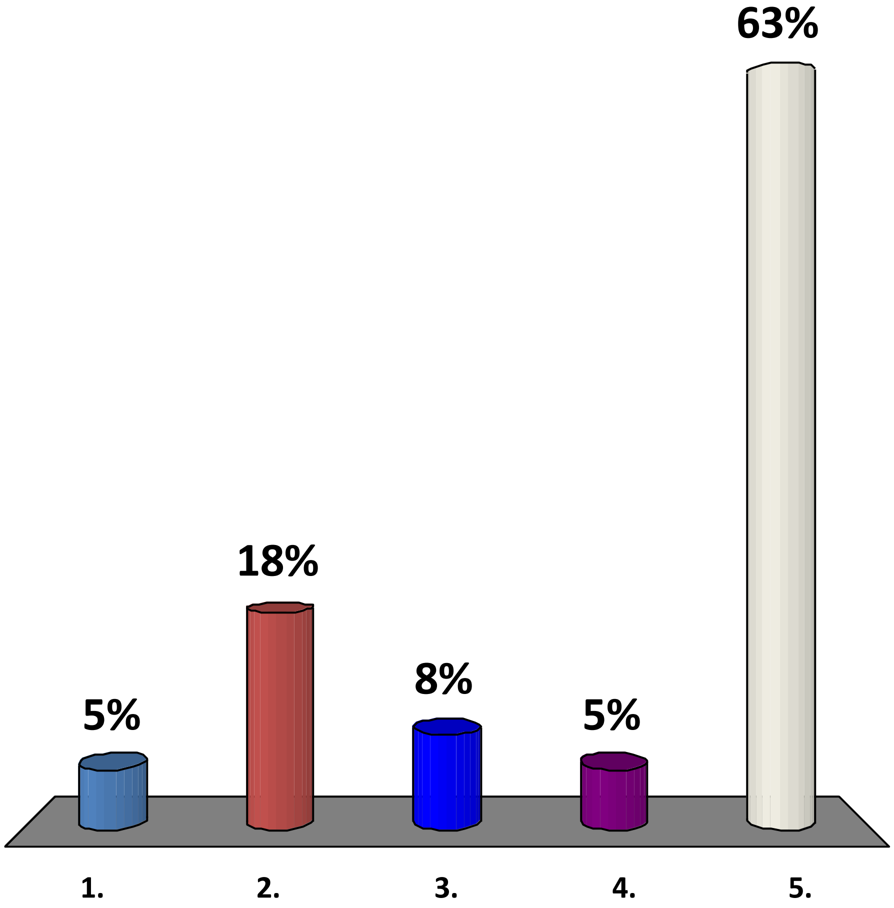
$= 40 m^3/d$

$V = 40\ m^3/d * 20d$

$= 800\ m^3$

Calculate the heath requirements

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



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

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

$* 1000\ kg/m^3$

$* (34\ °C – 10\ °C)$

$* 4200\ J/(kg.°C)$

$= 4032\ MJ/d$

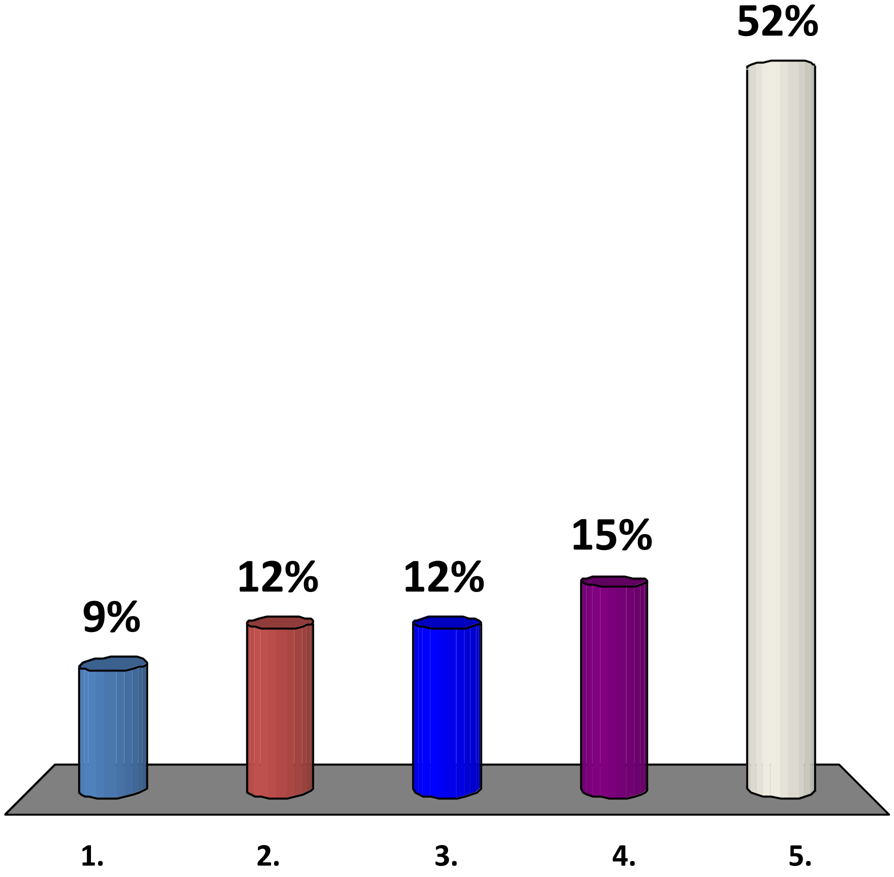
- Losses:
  - Surface of the digester = $2 * \pi * 4{,}6^2 + 2 * 4{,}6 * \pi * 12 = 480\ m^2$
  - Heat loss = $0.60 W/m^2.°C * 480\ m^2 * (34°C-10°C) * 3600\ s/h * 24\ h/d$

  = 597 MJ/d
- Total heat requirements = 4032 MJ/d + 597 MJ/d

  = 4629 MJ/d

Energy production?

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



CODin = 1560 kgCOD/d

COD degraded
= 1560 kgCOD/d * 0.35
= 546 kgCOD/d

Methane production
= 0,35 * 546
= 191.1 m³ CH_4/d

Total energy production
= 191.1 m³ CH4/d* 36.7 MJ/m³
= 7013 MJ/d
= 1948 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 it's unit processes

- Calculate operational parameters based on biokinetic values

- Estimate operational costs/gain of a WWTP