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University of Stavanger

Improving BOD removal at SNJ wastewater treatment plant by biological treatment at low temperature

Written by

Valeri Aristide Razafimanantsoa

Abstract

Nowadays, the use of microorganisms in wastewater handling known as 'biological treatment' becomes more and more popular. Better results can be achieved with this process. SNJ, one of the biggest chemical wastewater treatments in Norway, projects to use biological treatment in the future in order to meet the European requirement for discharge of urban wastewater, which is equal to 125 mg COD/l. The pilot study performed at the University of Stavanger during three months (January 2010 to March 2010) permitted to acquire all the parameters necessary for the design of the new plant. In this matter, a maximum specific growth rate of 0.68 d^{-1} had been found for the bacteria living in the wastewater, and with a decay rate of 0.07 d^{-1} during the cold period (5^{o}C). The bioreactor volume required for the treatment varies between 3000 m^3 to 190 000m^3 depending on the treatment methods chosen.

Keywords: *Wastewater, biological treatment, maximum specific growth rate, decay rate, bioreactor design*

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Θ: Temperature coefficient

μ: Specific growth rate (d-1)

μ_{max}: Maximum specific growth rate (d-1)

A: Surface area (m2)

BOD: Biochemical oxygen demand (mg/l)

BOD_{rem}: BOD load removed (KgBOD/d)

C_e: Effluent substrates (mg/l)

C_{in}: Influent substrates (mg/l)

C_N: Concentration of nitrogen (mg/l)

Co_2: Concentration of oxygen (mg/l)

COD: Chemical oxygen demand (mg/l)

COD_b: Biodegradable COD

COD_{up}: Unbiodegradable particulate COD

COD_{us}: Unbiodegradable soluble COD

C_s: Concentration of substrates (mg/l)

d: Day

D1 = DO of diluted sample immediately after preparation, mg/L,

D2 = DO of diluted sample after 5 d incubation at 20°C, mg/L,

E: BOD removal efficiency (%)

F: Recirculation factor

f_{cv}: Conversion factor (1.42 mgCOD/mgVSS)

f_d: Unbiodegradable residue in the cells

ISS: Inorganic suspended solids (mg/l)

k_c : Hydrolysis constant

K_d: Decay constant for heterotrophic organisms (d-1)

K_h: Hydrolysis constant (d-1)

k_h: Volumetric hydrolysis rate (gCOD/l.d)

K_N: Half-saturation constant for nitrogen (mg/l)

Ko_2: Half-saturation constant for oxygen (mg/l9

K_s: Half-saturation constant for substrate (mg/l)

K_x: Half-saturation coefficient for hydrolysis (mgCOD/mgCOD)

L_A: Surface area organic loading rate ($gBOD/m^2.d$)

L_h: Hydraulic loading rate (m3/m2.d)

L_v: Volumetric organic loading rate (KgBOD/m^3.d)

MLSS: Mixed liquor suspended solids (mg/l)

MLVSS: Mixed liquor volatile suspended solids (mg/l)

OUR: Oxygen utilization rate (mgO/l.h)

P: Decimal volumetric fraction of sample used

P_x: Waste production (kg)

Q: Average influent flow rate (m^3/d)

Q_r: Recycle flow rate (m3/d)

Q_w: Wasted flow rate (m3/d)

So: Influent BOD concentration (KgBOD/m^3)

SRT: Sludge retention time (d)

SS: Suspended solids (mg/l)

SVI: Sludge volume index (ml/g)

T: Temperature (^oC)

TOC: Total organic carbon (mg/l)

TSS: Total suspended solids (mg/l)

V: Volume (m3)

V_{ml}: Volume of mixed liquor (at concentration Xv mgVSS/l) (l)

VSS: Volatile suspended solid (mg/l)

V_{ww}: Volume of wastewater (l)

X: Suspended solids concentration (mg/l)

X_e: Effluent biomass concentration (mg/l)

X_E: Endogenous residue (mg/l)

X_H: Concentration of heterotrophic organisms (mg/l)

$X_{i,e}$: Unbiodegradable organic suspended solids in the effluent (mg/l)

$X_{i,in}$: Unbiodegradable organic suspended solids in the influent (mg/l)

$X_{i,r}$: Recycle unbiodegradable organic suspended solids (mg/l)

$X_{i,w}$: Wasted unbiodegradable organic suspended solids (mg/l)

X_{in}: Biomass concentration in the influent (mg/l)

X_r: Recycle biomass concentration (mg/l)

X_w: Wasted biomass concentration (mg/l)

Y or $Y_{x/s}$: Yield constant (gVSS/gCOD or gCOD/gCOD)

ΔO: Mass of oxygen utilized in RBCOD consumption per litre batch mixture (mgO/l)

μmax_{20}: Maximum growth rate at a standard temperature of 20^oC (d^{-1})

μmax_T: Maximum growth rate at a temperature T (d^{-1})

Introduction

To date the wastewater treatment policy in Norway has been focused to meet local and regional environmental quality objectives. The organic load into the receiving water was generally very low, resulting in low oxygen demand. Oxygen depletion due to discharge of urban wastewater was not a problem in that time. In the other hand, eutrophication was a huge threat, and phosphorus was the main limiting factor for algae growth. That is the reason why Norway has mainly been focused on phosphorus removal. Compared to the other methods available, chemical treatment was considered the most efficient way to deal with the problem.

According to NORVAR (2002), chemical precipitation plants represent 38 % of the total hydraulic capacity of Norwegian municipal wastewater plants, combined biological and chemical treatment for 28%, mechanical treatment for 31%, biological treatment plants for 1% and 2% for the other plants where the treatment method is unknown.

On 27 February 1998, the European Commission issued directive 98/15/EC amending directive 91/271/EEC to clarify the requirements of the directive in relation to discharges from urban wastewater treatment plants to sensitive areas which are subject to eutrophication. So prior to discharge, wastewater should contain 25 mg/l BOD and 125 mg/l COD in maximum (or 75% BOD_5 and 70% COD removal in term of efficiency) after secondary treatment. Chemical coagulation plants such as SNJ face sometimes problems to meet the new requirements. A reconstruction of the treatment plant is judged necessary to achieve a more efficient BOD removal. For this reason, SNJ plan to take account of biological treatment in the future, which is the main objective of this project to test biological treatment with SNJ wastewater at different temperature in order to establish the design parameters, which will be used further to estimate the volume required for the treatment of wastewater by biological means. This project is entitled **Improving BOD removal at SNJ wastewater treatment plant by biological treatment.**

This work is divided in five main sections. Information about SNJ and the different variants of biological processes are presented in the first section. Description of the experiment and the different methods used during this study are the core of the second section. Presentation of the results and discussion are covered in the third section. Simulation with AQUASIM software will be elaborated in the fourth section. Design calculations of activated sludge and aerobic biofilm reactor will be the last section of this book.

1. Background and literature

1.1. Sentralrenseanlegg Nord-Jæren (SNJ)

a. General information

Sentralrenseanlegg Nord-Jæren (SNJ) is one of the largest wastewater treatment plants in Norway. SNJ is located at Mekjarvik in Randaberg (10 km north of Stavanger). The plant was put into operation on 13 March 1992.This plant use chemical treatment for the removal of phosphorus and suspended solids. The plant receives wastewater from different municipalities such as Randaberg, Stavanger, Sola, Sandnes and Gjesdal. Wastewater is brought to the treatment plant in a main pipeline system from Figgjo in Gjesdal municipality to Mekjarvik, a total of approx. 35 km. The tunnel has a volume of 77,000 m^3 and acts as equalization magazine during rainfall periods. Wastewater contains both sewage and surface water (rain, surface), since much of the old sewer system is combined system.

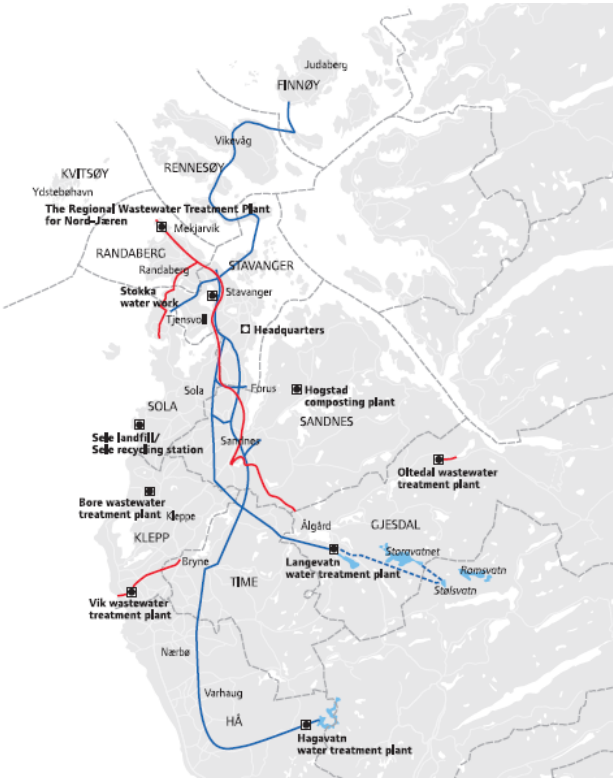

Figure 1: Wastewater collect facilities
Source: IVAR, 2010

b. Activities

SNJ is composed of wastewater treatment plant, anaerobic sludge digestion, dewatering and drying plant and finally the odor treatment plant (IVAR, 2010).

- *Wastewater treatment plant*

First, wastewater is pumped by a sump pump to the grid stations located at 20 m above the tunnel. The pumping station consists of four pitched dry pumps each with a capacity of 600 l/s to 20 mVS. Each pump has its own path and amount of wire gauge.

Next, the wastewater goes to the first stage of treatment, which is screening and sand trap. During this stage, coarse particles are separated in the 6 pieces staircase shaker with 3 mm of aperture, while sands are removed in the two parallels aerated sand traps. Iron chloride is added at the entrance to the sand trap pool to promote the formation of large particles, which can be settled by means of its own weight. Finally, the flocs are separated from the water

phase in the sedimentation basins composed of four vessels. Each vessel consists of two parallel pools that are 7 m wide, 67.6 m long and 4.8 m depths. Finally, the purified water is discharged in Håsteinfjorden (1.6 Km from shore) at 80 m depth, whereas the sludge is pumped from the sedimentation basins to two anaerobic digesters with a volume of 3500 m^3 each. This sludge has a solids content of approx. 5%.

- *Biogas plant*

The sludge undergoes the fermentation process where anaerobic bacteria break down organic matter without access to oxygen. This process reduces volatile suspended solids (VSS) and produces biogas, which normally consists of about 70 - 80% methane. Biogas undergoes a simple pretreatment for the removal of water, foam and particles before it is fed to boiler plants for the production of steam.

- *Dewatering and drying plant*

Dewatering occurs in three centrifuges in which 2 can be operated simultaneously. Each centrifuge has a capacity of about 25 m^3/h. Polymers are added to the sludge. Normally 30-32% solids content were achieved after dewatering. The dewatered sludge is transported to the sludge drying plant by two mud pumps.

The drying plant consists of two driers of which operated continuously and the other serves as a dry spare for longer outages.

The solids content after centrifugal dewatering and thermal drying is about 85%. The dried product is formed into small pellets (biopellets) that are simple to store, handle and transport. The final products are dust-free, with no annoying odor or pathogens and meet the governmental standard for non-agricultural land use.

- *Odor treatment*

SNJ installed odor removal system for the process section that emits strong odors. This applies to the biogas plant, sludge reception and drying facilities. The exhaust gases from the biogas plant and sludge reception are removed by a biofilter where the odor substances are broken down by separate bacterial cultures.

At SNJ, the entire facility is built with two separate and parallel lines so that it is possible to do experiments with other solutions, or to run maintenance operations without interference.

Attempts are made continuously to ensure that the plant will be operated in a technically and economically optimal way.

c. Constraints

When SNJ was built in 1992, it was designed for 240 000 person equivalents (p.e). And over time, the number of inhabitants increases twelve-monthly. In 2050, SNJ expect to receive wastewater corresponding to 500 000 p.e; which means more organic loading into the plant (30 000 Kg BOD/day). To deal with the situation, SNJ plan to extend the plant and change their way of treating the wastewater this according to the 1991 Urban Wastewater Treatment Directive.

1.2. Alternatives for BOD removal

Dissolved organics are generally treated with biological processes. The more common systems are aerobic (with oxygen) and include aerobic or facultative pond, biofilm reactor, and activated sludge processes (Corbitt, 2004). All these processes rely on the ability of microorganisms to convert organic wastes into stabilized, low-energy compounds (Hammer and Hammer Jr., 2001).

a. Biofilm

In biofilm systems, microorganisms attach themselves in a thin layer, onto a support medium. The latter may be in the form of a fixed bed or moving bed (NG WunJern, 2006).The table below summarizes the different types of biofilm processes with some applicable examples.

Table 1: Variants of Biofilm processes

Processes	Examples
Non-submerged attached growth processes	Trickling filters
Movable filter medium	Kaldnes, Rotating biological contactors (RBCs), fluidized- bed bioreactors (FBBR), Meteor
Stationary filter medium	Biofor and Biostyr process

Source: adapted from Henze et al.(2002)

- *Trickling filters*

Trickling filter is the conventional biofilm reactor. It has been used to provide biological wastewater treatment of municipal and industrial wastewater for nearly hundred years (Henze et al., 2002).

Trickling filters are classified by hydraulic and organic loading. Moreover, the expected performance and the construction of the trickling filter are determined by the filter classification. Filter classifications include standard rate, intermediate rate, high rate, super high rate (plastic media), and roughing rate types. Standard rate, high rate, and roughing rate are the filter types most commonly used. Table 2 resumes the characteristics of the different types of trickling filters.

Table 2: Typical characteristics of the different types of trickling filters (at 20°C)

Operational conditions	Low rate	Intermediate rate	High rate	Super high rate	Roughing
Packing medium	Stone	Stone	Stone	Plastic	Stone/Plastic
Hydraulic loading rate ($m^3/m^2.d$)	1 – 4	3 – 10	10 – 40	12 – 70	45 – 185
Organic loading rate ($KgBOD/m^3.d$)	0.1 – 0.4	0.2 – 0.5	0.5 - 1	0.5 – 1.6	Up to 8
Effluent recycle	Minimum	Occasional	Always ([1])	Always	Always
Flies	Many	Variable	Variable	Few	Few
Biofilm loss	Intermittent	Variable	Continuous	Continuous	Continuous
Depth (m)	1.8 – 2.5	1.8 – 2.5	0.9 – 3	3 – 12	0.9 – 6
BOD removal (%)([2])	80 – 85	50 – 70	65 – 80	65 – 85	40 – 65
Nitrification	Intense	Partial	Partial	Limited	Absent

Source: Adapted from Metcalf and Eddy (1991)

- *Rotating Biological Contactors*

The rotating biological contactor (RBC) is a biological treatment system and is a variation of the attached growth idea provided by the trickling filter. Still relying on microorganisms that grow on the surface of a medium, the RBC is instead a fixed film biological treatment device (Spellman, 1999). The basic biological process is similar to that occurring in the trickling filter. An RBC consists of a series of closely spaced (mounted side by side), circular, plastic (synthetic) disks that are typically about 11.5 ft in diameter and are attached to a rotating horizontal shaft. Approximately 40% of each disk is submersed in a tank containing the wastewater to be treated. As the RBC rotates, the attached biomass film (zoogleal slime) that grows on the surface of the disks moves into and out of the wastewater. While submerged in the wastewater, the microorganisms absorb organics; while they are rotated out of the wastewater, they are supplied with needed oxygen for aerobic decomposition. As the zoogleal

([1]) Effluent recycle is usually unnecessary when treating effluents from anaerobic reactors

([2]) Typical BOD ranges for TF fed with effluents from primary settling tanks. Lower efficiencies are expected for TF fed with effluents from anaerobic reactors, although overall efficiency is likely to remain similar.

slime reenters the wastewater, excess solids and waste products are stripped off the media as sloughing. These sloughing are transported with the wastewater flow to a settling tank for removal. Table 3 shows the design criteria for RBCs.

Table 3: Design criteria for RBCs (at 20°C)

Operational conditions	BOD removal	BOD removal and nitrification	Separate nitrification
Hydraulic loading rate ($m^3/m^2.d$)	0.08 – 0.16	0.03 – 0.08	0.04 – 0.10
Surface Organic loading rate (SOLR) ($gBOD_{soluble}/m^2.d$)	3.7 - 9.8	2.4 – 7.3	0.5 – 1.5
Surface Organic loading rate ($gBOD/m^2.d$)	9.8 – 17.2	7.3 – 14.6	1.0 – 2.9
Maximum SOLR in first stage ($gBOD_{soluble}/m^2.d$)	19 – 29 (14*)	19 – 29 (14*)	-
Maximum SOLR in first stage ($gBOD/m^2.d$)	39 – 59 (30*)	39 – 59 (30*)	-
Surface nitrogen loading rate ($gN\text{-}NH_4^+/m^2.d$)	-	0.7 – 1.5	1.0 – 2.0
Hydraulic detention time (h)	0.7 – 1.5	1.5 - 4	1.2 – 2.9
BOD in the effluent (mg/l)	15 - 30	7 - 15	7 - 15
$N\text{-}NH_4^+$ in the effluent (mg/l)	-	< 2	< 2

*typical design values
Source: adapted from Metcalf and Eddy (1991)

The RBC normally produces a high-quality effluent: 85-95% (BOD_5), Suspended solids removal up to 85-95%.

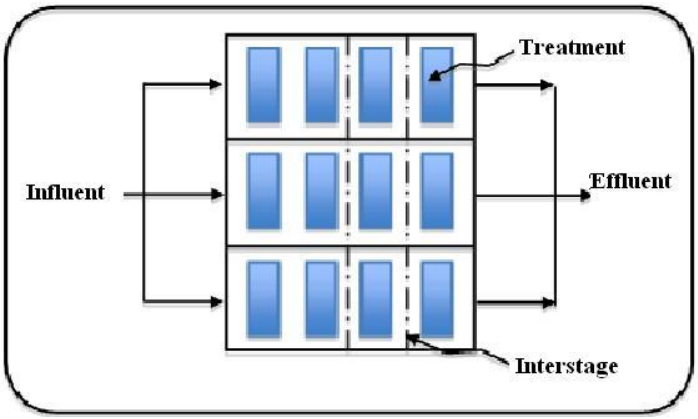

Figure 2: Typical configuration of RBCs
Source: adapted from Leslie and al. (1999).

- *Kaldnes process*

Kaldnes process is based on biofilm and activated sludge principles. Professor Halvard Odergard at Trondheim University of Science and Technology developed this process in 1989 and it was the first wastewater technology in Norway having nitrogen removal. Kaldnes use a wheel plastic (polyethylene), with a density slightly below that of water, as a biofilm carrier (biocarrier), and which were kept in suspension and in continuous movement within the bioreactor (Welander U. and B. Mattiasson, 2003). These biocarrier were designed to provide a large protected area for the biofilm and optimal conditions for the microorganisms.

Kaldnes can be used as a preliminary treatment stage, as a combined IFAS hybrid stage or as a polishing step. Unlike the activated sludge process, Kaldnes can handle extremely high loading rate without any problems of clogging. The dead organisms on the outside of biocarrier are removed during its movement within the bioreactors and make a space for a new generation of bacteria to colonize.

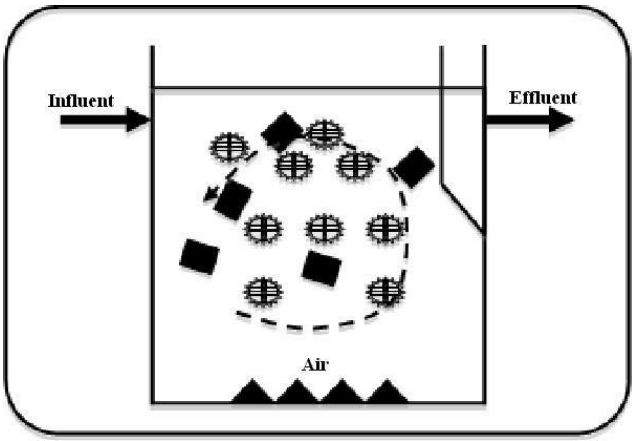

Figure 3: Kaldnes process

Source: adapted from Welander U. and B. Mattiasson (2003)

Different ranges of Kaldnes biocarrier are available in the market as shown in table 5.

Table 4: Different types of biocarrier

Model	Length (mm)	Diameter (mm)	Protected surface (m^2/m^3)	Total surface (m^2/m^3)
K1	7	9	500	800
K3	12	25	500	600
Natrix C2	30	36	220	265
Natrix M2	50	64	200	230
Biofilm-Chip M	2,2	48	1200	1400
Biofilm-Chip P	3,0	45	900	990

Source: Adopted from www.anoxkaldnes.com (2006)

Kaldnes is also used in combination with activated sludge process (combined system).

- *Fluidized-Bed Bioreactor (FBBR)*

A fluidized-bed bioreactor is one in which biofilm grows attached to small carrier particles that remain suspended in the fluid by the drag forces associated with the upward flow of water. The wastewater is fed upward to a bed of 0.4 – 0.5 mm sand or activated carbon (Tchobanoglous and al., 2003). Bed depths are in the range of 3 to 4m and the specific area is about 1000 - 2000 m^2/m^3 of reactor volume. The up flow velocities are 30 to 36 m/h and the hydraulic retention time range from 5 to 20 min.

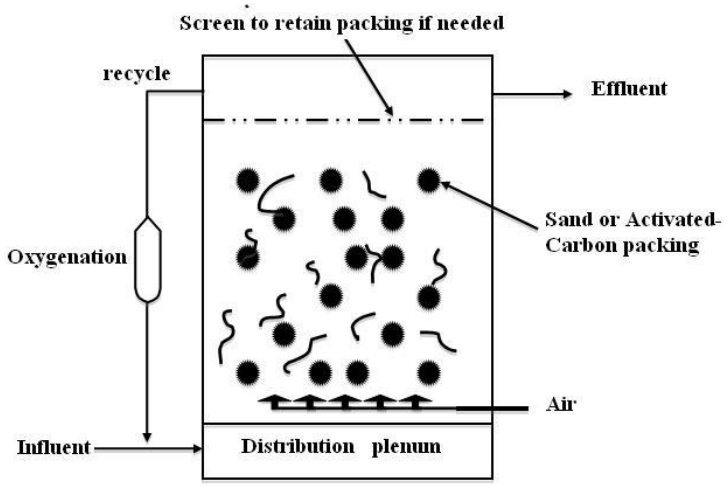

Figure 4: FBBR process
Source: adapted from Tchobanoglous (2003)

- *BIOFOR®*

BIOFOR® is one of the Degrémont technologies available nowadays. In this process the effluent to be treated enters continuously from the bottom of the reactor as shown in the figure 4 and is distributed over the entire filter surface area by the nozzle under drain and aeration. The water passes through a Biolite filter media, which retain the suspended solids. The media provides surfaces for biofilm growth and BOD and nitrogenous pollutant are eliminated through this filter media during the filtration cycle (Degremont, 2009).

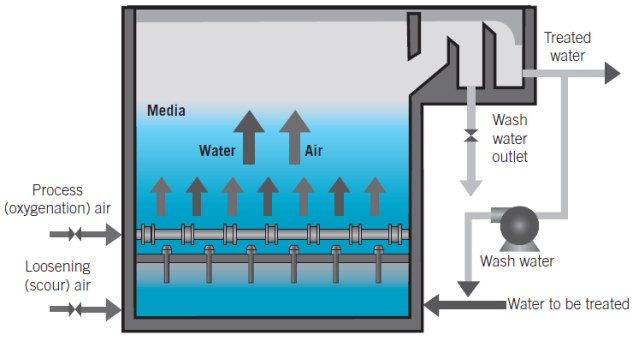

Figure 5: Biofor process
Source: Degremont (2009)

The use of a co-current upflow design helps to limit odor generation since the treated water is situated at the surface of the filter (in contact with the atmosphere), and the untreated water enters at the bottom of the filter.

The number of filters in filtration service is according to the flow entering the plant. During low flow periods, off-duty filters are aerated

periodically to maintain the biomass in optimum condition. Since filters can be taken out of service when not required, operating costs (due to process air production) can be reduced. The design loading for the treatment is shown in the table 4.

Table 5: Design loading for BIOFOR (at 20°C)

Application	Performance	
BOD removal	Filtration rate	3-12 m/h
	Loading	2 – 8 kg BOD_5/m^3 per day
Nitrification	Filtration rate	1.2 – 6.6 gpm/ft^2 (3-16 m/h)
	Loading	0.5 – 2 kg NH_3 –N/m^3 per day
Pre-denitrification	Filtration rate	10 -35 m/h
	Loading	3 – 7 kg NO_3 - N/m3 per day
Post-denitrification	Filtration rate	10 -30 m/h
	Loading	1–1.5 kg/ NO_3 -N/m^3 per day

Source: Infilco Degrémont inc., 2009.

This technology can get effluents with TSS and BOD less than 10 mg/L, ammonia at 1.5 mg/L NH_3-N, Nitrate down to 1.5 mg/L NO_3-N and total Nitrogen about 3 mg/L TN. The oxygen transfer efficiency is typically 15 - 25%.

b. Activated Sludge

Horan (1989) defined the activated sludge process as a suspended growth system comprising a mass of microorganisms constantly supplied with organic matter and oxygen. This process is widely used worldwide for the treatment of domestic and industrial wastewater, in situations where high effluent quality is necessary (Sperling, 2007). According to Tchobanoglous and al. (2003), a number of AS processes and design configuration have evolved due to new regulations for effluent quality, technological advances, better understanding of microbial processes and to reduce costs. We can have complete-mix activated sludge (CMAS), plug-flow (conventional, high-rate aeration, step feed, contact stabilization, two-sludge, high-purity oxygen, Kraus process, conventional extended aeration), extended aeration (oxidation ditch, orbal, countercurrent aeration system, biolac process) and the sequentially operated systems such as sequentially batch reactor (SBR), cyclic activated sludge system (CAAS), Batch decant reactor- intermittent cycle extended aeration system (ICEAS).

Table 6: Main characteristics of the activated sludge systems used for the treatment of domestic sewage (at 20°C)

		Type	
General item	**Specific item**	**Conventional**	**Extended aeration**
Sludge age	Sludge age (day)	4 – 10	18 – 30
F/M ratio	F/M ratio (KgBOD/KgMLVSS.d)	0.25 – 0.50	0.07 – 0.15
Removal efficiency	BOD (%)	85 – 95	93 – 98
	COD (%)	85 – 90	90 – 95
	SS (%)	85 – 95	85 – 95
	Ammonia (%)	85 – 95	90 – 95
	Nitrogen (%)([3])	25 – 30	15 – 25
	Phosphorus (%) ([3])	25 – 30	10 – 20
	Coliforms	60 – 90	70 – 95
Area required	Area (m^2/inhabitant)([4])	0.2 – 0.3	0.25 – 0.35
Total volume	Volume (m^3/inhabitant)[5]	0.10 – 0.12	0.10 – 0.12
Energy ([6])	Installed power (W/inhabitant)	2.5 – 4.5	3.5 – 5.5
	Energy consumption (kW.h/inhabitant.year)	18 – 26	20 – 35
Volume of sludge ([7])	To be treated (L sludge/inhabitant.d)	3.5 – 8.0	3.5 – 5.5
	To be disposed of (L sludge/inhabitant.d)	0.10 – 0.25	0.10 – 0.25
Sludge mass	To be treated (gTS/inhabitant.d)	60 – 80	40 – 45
	To be disposed of (gTS/inhabitant.d)	30 – 35	40 - 45
Hydraulic retention time	HRT (h)	6 – 8	16 – 24

Source: adapted from Sperling (2007)

Nowadays, various types of packing materials for biofilm growth are used in the aeration tank of activated sludge to combine biofilm and activated sludge. Typical examples of that kind of processes are Captor, Limpor and Kaldnes or moving bed bioreactor (MBBR).

([3]) Larger efficiencies can be reached in the removal of N and P

([4]) Smaller areas can be obtained by using mechanical dewatering. The area values represent the area of the whole WWTP, not just of the treatment unit.

([5]) The total volume of the units includes primary sedimentation tanks, aeration tanks, secondary sedimentation tanks, gravity thickeners and primary and secondary digesters. The dewatering process assumed in the computation of the volumes is mechanical. The need for each of the units depends on the variant of the activated sludge process.

([6]) The installed power should be enough to supply the O2 demand in peak loads. The energy consumption requires a certain control of the O2 supply, to be reduced at times of lower demand.

([7]) The sludge volume is a function of the concentration of total solids, which depends on the processes used in the treatment of the liquid phase and the solid phase. The upper range of per capita volumes of sludge to be disposed of is associated with dewatering by centrifuges and belt presses (lower concentration of TS in the dewatered sludge), while the lower range is associated with drying beds or filter presses (larger TS concentration).

c. Combined systems (Activated Sludge and Biofilm)

- *METEOR® (IFAS/MBBR process)*

METEOR® process is a combination of fixed-film technology and suspended growth technology (conventional activated sludge) together into one hybrid system known as IFAS or integrated fixed film activated sludge (Degremont, 2009). Polyethylene biofilm carriers are used in this process, providing a large internal surface area for the growth of microorganisms. The METEOR® technology achieves high removal rates in a small volume.

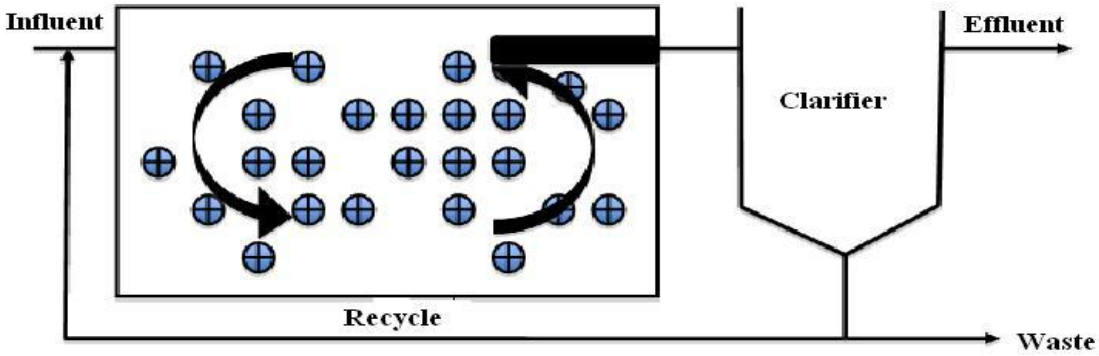

Figure 6: Meteor process
Source: adapted from Degremont (2009)

With this kind of technology, the capacity of activated sludge basins can be increased by 100% to 200% with an in-basin retrofit; upgrade existing BOD removal facilities to full nitrification and total nitrogen removal in response to new regulatory requirements: ammonia removal to < 1 mg/L NH_3-N, Nitrate removal to < 1 mg/L NO_3-N and Total Nitrogen removal to < 3 mg/L TN. Better settling of suspended solids than conventional activated sludge will also be achieved.

1.3. Modeling and design of an activated sludge

The following schematic diagram in Figure 7 shows an activated sludge system that the mass balances of biomass and substrate mass balances are set up on (Ydstebø, 2009).

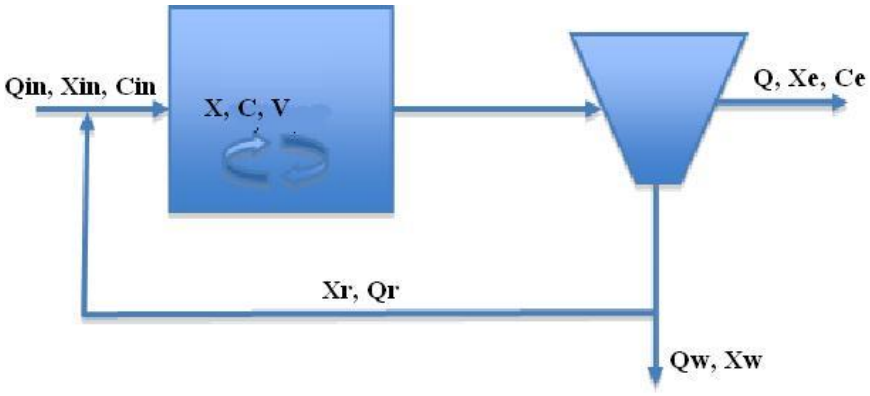

Figure 7: Activated sludge process

a. Effluent concentration of COD

The concentration of COD in the effluent is the sum of remaining soluble biodegradable COD known as readily biodegradable COD, unbiodegradable soluble COD in the influent and finally the COD in TSS/VSS in the effluent (1.42g COD/gVSS).

The remaining RBCOD can be determined by solving the biomass mass balance.

Accumulation = Inflow - outflow + biomass production - decay – waste

$$V\frac{dx}{dt} = -Q(X_{in} - X_e) + (\mu - k_d)XV - Q_w X_w$$

Dividing by V

$$\frac{dx}{dt} = \mu X - \frac{Q(X_{in} - X_e)}{V} - k_d X - \frac{Q_w X_w}{V}$$

Assuming steady state $\frac{dx}{dt} = 0$, therefore

$$0 = \mu X - k_d X - \frac{Q_w X_w}{V}$$

$$\frac{Q_w X_w}{V} = (\mu - k_d)X$$

$$\frac{Q_w X_w}{XV} = \mu - k_d$$

$\frac{Q_w X_w}{XV}$ = Sludge wasted (kg/d)/Mass of sludge in the reactor (kg) which is equal to the inverse of the sludge retention time (SRT), thus:

$$\frac{1}{SRT} = \mu - k_d$$

The growth rate is according to Monod's equation $\mu = \mu_{max} \cdot \frac{C_s}{Ks + C_s}$

$$\frac{1}{SRT} = \mu_{max} \cdot \frac{C_s}{Ks + C_s} - k_d$$

$$\boldsymbol{C = \frac{K_s \cdot (k_d + \frac{1}{SRT})}{\mu_{max} - (k_d + \frac{1}{SRT})}}$$

In figure 7, wasting of the sludge is on the underflow. Wasting from the bioreactor is also an option and makes it easier to maintain a fixed SRT because it is independent of the sludge concentration. Since $X=X_w$, SRT becomes as a ratio of the bioreactor volume and the volume wasted.

$$SRT = \frac{VX}{Q_w X_w} = \frac{V}{Q_w}$$

b. Sludge in the bioreactor

The sludge in the bioreactor is composed of the active organisms in the system, which is the net effect of growth on substrate (biodegradable COD), cell-death and inert residue from dead cells. The remaining slowly biodegradable COD and inert COD from influent are attached to the flocs. In addition contains the sludge inorganic particles determined as inorganic fraction in TSS/VSS analysis.

- *Biomass concentration and mass*

It can be derived from the substrate mass balance:

Accumulation = inflow – outflow – removal

$$V.\frac{dC}{dt} = Q\ (C_{in} - C_e) - \mu \frac{X.V}{Y}$$

With $\mu - k_d = \frac{1}{SRT}$ ➔ $\mu = k_d + \frac{1}{SRT}$

At steady state $\frac{dC}{dt} = 0$

$$0 = Q\,(C_{in} - C_e) - \frac{XV}{Y}.(k_d + \frac{1}{SRT})$$

$$X = \frac{Q.(C_{in} - C_e).Y}{V.(k_d + \frac{1}{SRT})}$$

Multiplying with SRT on the right side gives the following equation for the biomass concentration (mg/l):

$$X = \frac{Q.(C_{in} - C_e).Y.SRT}{V.(SRT\,.k_d + 1)}$$

The total mass of biomass is the product of concentration and bioreactor volume:

$$\boldsymbol{MX = X.V = \frac{Q.(C_{in} - C_e).Y.SRT}{(SRT\,.k_d + 1)}}$$

- *Unbiodegradable organic suspended solids in influent (Xi,in)*

Accumulation = inflow - outflow – waste

$$V\frac{dx_i}{dt} = Q\,(X_{i,in} - X_{i,e}) - Q_w.X_{i,w}$$

Assume steady state and $X_{i,e} = 0$

Assume sludge waste from the bioreactor, then $X_{i,R} = X_{i,w}$

And $SRT = \frac{V}{Q_w}$

$$0 = Q.X_{i,in} - Q_w.X_{i,w}$$

$$0 = Q.X_{i,in} - \frac{V.X_{i,R}}{SRT}$$

$$X_{i,R} = Q.X_{i,in}.\frac{SRT}{V}$$

Concentration:

$$X_{i,R} = X_{i,in}.\frac{SRT}{t_h}$$

Mass:

$$\boldsymbol{MX_{i,R} = V.X_{i,R} = Q.X_{i,in}.SRT}$$

Considering inorganic solids in the influent ($X_{ii,in}$), the same expression will be found:

$$X_{ii} = t_H .X_{i,in} . SRT$$

This is normally not calculated but determined based on correlation of MLVSS values as determined at a range of SRT's (Ekama, 1986).

- *Unbiodegradable organic solids from dead organisms*

After death, a part of the dead organisms will be oxidized and the rest will remain unbiodegradable.

$$\Delta X = \Delta X_E + \Delta O$$

$$\Delta X = f_d.\Delta X + (1\text{-}f_d)\Delta X$$

Decay rate $(\frac{dX}{dt})_d = -k_d.X$

Production of endogenous residue $\frac{dX_E}{dt} = f_d.k_d.X$

Accumulation = Production – Waste

$$V.\frac{dX_E}{dt} = f_d.k_d.X.V - Q_w . X_{E,w}$$

By assuming steady state and sludge waste from the bioreactor, the concentration in the bioreactor $X_{E,R}$ and waste stream $X_{E,w}$ is the same; and SRT = V/Q_w.

$$0 = f_d.k_d.X.V - \frac{X_{E,R}.V}{SRT}$$

$$MX_{E,R} = X_{E,R} . V = f_d . k_d . MX . SRT$$

So the composition of the organic sludge in the bioreactor becomes

Organic fractions = biomass + unbiodegradable organic in wastewater + endogenous residue

$$MLVSS = X + X_{i,R} + X_{E,R}$$

$$MVSS = MLVSS . V = MX + MX_{i,R} + MX_{E,R}$$

The inorganic fraction and thus the total suspended solids concentration (MLSS) is found by analyzing the MLVSS / MLSS ratio, which is found to be within the range 0.7 – 0.8.

c. Sludge production

The daily production of sludge is given by the following equation:

$SRT = V.X/Q_w .X_w$

$$P_x = Q_w . X_w = \frac{V . MLSS}{SRT}$$

d. Oxygen demand

In a completely mixed aerobic bioreactor, oxygen is supplied to satisfy the oxygen requirement for the oxidation of the carbonaceous organic matters (oxidation of the organic carbon to supply energy for bacterial growth and endogenous respiration of the bacterial cells) and for the oxidation of nitrogenous matters (Sperling, 2007). The oxygen consumed for the degradation of substrate is given by the equation

$$MO_S = Q . \Delta COD (1 - Y)$$

(1 – Y) is the fraction of substrate not used in synthesis of biomass (growth).

While the endogenous respiration consumed:

$$MO_E = (1 – f_d).k_d.X.V$$

Therefore, the total oxygen consumption for the removal of organic matters becomes

$$\mathbf{MO_T = MO_S + MO_E}$$

e. Volume of the bioreactor

Based on the biomass generation, we calculate the required volume of the bioreactor.

$$MVSS = MX + MX_E + MX_i$$

$$MTSS = \frac{MVSS}{\frac{MLVSS}{MLSS} ratio\ (0.7 - 0.8)}$$

$$\boldsymbol{V = \frac{MTSS}{MLSS}}$$

Where :

MTSS: Total mass of solids in the bioreactor

MLSS: Mixed liquor suspended solids concentration set by the designer (typical 2- 5000 mg/l).

The design procedure can be summarized in five steps:

Step 1: Select SRT value

Step 2: Calculate effluent COD (to compare with effluent requirements)

Step 3: Calculation of total mass

Step 4: Select MLSS concentration

Step 5: Calculation of the bioreactor volume

1.4. Design of aerobic biofilm reactors

Several models can be used for the dimensioning of biofilm reactors (Kommedal, 2009):

- Empirical model
- Hydraulic loading rate
- Organic loading rate
- Steady state one dimensional biofilm model
- Dynamic biofilm model (e.g. AQUASIM)

In this study, design will be based on organic loading rate and hydraulic loading rate, similar to the loading factors presented in tables 2 to 4. Temperature correction will be applied during the design because the values given in table 2 to 4 are for the design of plants at 20^{o}C. The typical temperature coefficient used for the design of carbonaceous BOD system is 1.035 (WEF, 1998).

a. Hydraulic loading rate

The hydraulic loading rate L_h correspond to the volume of wastewater applied daily to the biofilm reactor, including recirculation, per unit surface area of biofilm or per unit of reactor cross-sectional area.

$$L_h = \frac{Q}{A}$$

Where:

L_h: hydraulic loading rate (m3/m2.d)
Q: average influent flow rate (m3/d)
A: surface area of the packing medium (m2)

b. Organic loading rate

Volumetric L_v organic load refers to the amount of organic carbons applied daily to the biofilm reactor per unit of reactor volume.

$$L_v = \frac{Q \times S_o}{V}$$

Surface area organic load (L_A) refers to organic load on surface area of the packing medium.

$$L_A = \frac{Q \times S_o}{A}$$

Where:

L_v: volumetric organic loading rate (KgBOD/m^3.d)
L_A: surface area organic loading rate (gBOD/m^2.d)
Q: average influent flow rate (m^3/d)
So: influent BOD concentration (KgBOD/m^3)

c. BOD removal efficiency

The empirical model for the estimation of the BOD removal efficiency for trickling filters is

$$E = \frac{1}{1 + 0.443\sqrt{\frac{L_v}{F}}}$$

Where:

E: BOD removal efficiency (%)

Lv: volumetric organic loading rate (KgBOD/m3.d)

F: recirculation factor

$$F = \frac{1 + R}{(1 + \frac{R}{10})^2}$$

Where:

R: recycle ratio (0 – 2)

d. Sludge production

The amount of sludge produced during the treatment can be estimated by means of the following equation.

$$P_x = Y \times BOD_{rem}$$

Where:

Px: sludge production (KgTSS/d)

Y: yield coefficient (KgTSS/Kg $BOD_{removed}$)

BOD_{rem}: BOD load removed (KgBOD/d)

The values of the yield for a biofilm reactors operating with high rate and without nitrification are in the range from 0.8 – 1 KgTSS/Kg $BOD_{removed}$.

e. Sludge retention time

Aerobic biofilm reactors are usually operated with a long sludge age, which vary from 15 to 60 days, depending on the rate of biofilm loss from the reactor.

2. Methodology

2.1.Operation and Control

Three experiments have been conducted for this study during the period of January to March. The three bioreactors were fed with the same wastewater from SNJ but the temperature was varied from 5°C to 20°C. The first bioreactor (20°C) had a volume of 4 liters and the rest (reactor 2 at 5°C and reactor 3 at 8°C) 1.5 liters each. At the first time, reactor 1 was fed with 4 liters of wastewater and we fed it with 2 to 2.5 liters a day while reactor 2 and 3 were fed with 1.2 liters every day.

When we started this experiment, all reactors were only fed with wastewater. Parameters like temperature, pH, and conductivity were measured daily for the three bioreactors. The nutrient concentrations were also determined in order to make sure that all the environmental factors permit the growth of microorganisms.

Two weeks later, about 1 g/l of sugar were added in each bioreactor to boost the growth of microorganisms. This kind of practice was used when we judged that the growth of microorganisms was really slow. About one month later, there was enough biomass to run the experiment. In addition to the physical and chemical measurements, Oxygen utilization rate (OUR) was measured, at least 5 times a day, to see how active the bacteria were. Factors such as temperature, pH, oxygen, OUR, conductivity, solids and TOC were recorded every day. A few measurements were done for the BOD, COD and nutrients (phosphorus and nitrogen). For the primary influent, we measured pH, conductivity, BOD, COD, and Suspended solids.

Cleaning of the bioreactors was done with 5% HCl every two weeks. The aim of this cleaning is to remove all biofilm growing on the diffuser and walls, which may interfere with the growth.

2.2.Analytical methods

a. Measurements of physical and chemical parameters

Physical and chemical parameters such as temperature, oxygen, pH and conductivity are key factors for the success of biological wastewater treatment, because bacteria's life depends on it.

- *Temperature and Dissolved Oxygen*

Temperature and oxygen was measured with an Oxymeter OXI 330i provided with a galvanic oxygen sensor (CellOx 325), which can measure an oxygen concentration within the range of 0 to 50 mg/l (resolution 0.1 mg/l). It was calibrated before use.

- *pH and Conductivity*

pH and conductivity was measured with a multi-parameters apparatus with reference Multi340i.

- *Solids analysis (Standard method by Clesceri and al., 1998)*

Total suspended solids (TSS) was determined by filtering a well-mixed sample with known volume through a weighed standard glass-fiber filter (GF/C glass –fiber filters with 1 µm pore size) and then the residue retained on the filter was dried to a constant weight at 103 to 105°C at least for two hours. The increase in weight of the filter represented the total suspended solids.

Calculation

$$\text{mg total suspended solids/L} = \frac{(A - B) \times 1000}{\text{sample volume, mL}}$$

where:
A = weight of filter + dried residue, mg, and
B = weight of filter, mg.

After weighing the residue retained on the filter, was put in the oven at 550^{o}C for 30 min and weigh it again. From that we get the inorganic suspended solids (ISS). So knowing the TSS and ISS, we can calculate the volatile suspended Solids (VSS).

- *Oxygen Utilization Rate (OUR)*

OUR was done by pouring MLSS in a sealed Erlenmeyer, measure the oxygen consumption over time until 2 mg/l of oxygen is left in the sample. Afterwards, put the results in a excel sheet and make a graph of the oxygen consumption over time. OUR was given by the slope of the graph.

- *Sludge Volume Index (SVI)*

Sludge volume index is defined as the volume of sludge in milliliters occupied by 1g of activated sludge (WEF, 1994). Pouring a mixed liquor sample in a graduated cylinder and measuring the settled volume after 30 min and the corresponding sample MLSS concentration obtain SVI.

SVI = (30-min settling volume / MLSS) * 1000

Units:
SVI (g/ml)
Volume (mL/L)

MLSS (mg/l)

- *Phosphorus and Nitrogen*

The amount of phosphorus and dissolved nitrogen such as ammonia (NH_4), nitrite (NO_2) and nitrate (NO_3) can be determined directly on the ion chromatography (Dionex ICS-3000). All samples are filtered with 0.2µm-syringe filter before the analysis in order to remove the remaining solids from the first filtration (with 1 µm pore size).

Standard solutions made by K_2HPO_4, NH_4Cl, KNO_2 and KNO_3 were prepared within an appropriate range for phosphorus, ammonia, nitrite and nitrate respectively.

b. Measures of the organic strength

The primary determinant in the design of bioreactor is the organic content, which has to be removed from the wastewater. Three parameters can be used to characterize the organic matters: biological oxygen demand (BOD), chemical oxygen demand (COD), and total organic carbon (TOC). This latter is a measure of the organic carbon in wastewater, not like the BOD and COD, which is a measure of the oxygen demand for the degradation of the organic matter.

- *Total Organic Carbon (TOC)*

During the experiment, a Shimadzu total organic carbon analyzer model TOC 5000A has been used for the determination of TOC on filtered samples.

- *Biological Oxygen Demand (BOD)*

The BOD test is carried out by diluting the sample with oxygen saturated water, measuring the initial dissolved oxygen (DO) and then sealing the sample to prevent further oxygen dissolving in. The sample is kept at 20 °C in the dark to prevent photosynthesis (and thereby the addition of oxygen) for five days, and the dissolved oxygen is measured again. The difference between the final DO and initial DO is the BOD, as shown in the following formula *(Standard method by Clesceri and al., 1998)*.

$$\mathrm{BOD}_5,\ \mathrm{mg/L} = \frac{\mathrm{D}_1 - D_2}{P}$$

where

D1 = DO of diluted sample immediately after preparation, mg/L,
D2 = DO of diluted sample after 5 d incubation at 20°C, mg/L,
P: decimal volumetric fraction of sample used (0.05 for this experiment)

- *Chemical Oxygen Demand (COD)*

When measuring the COD, sample and reagents are added into the HACH vials in the following order: 2.5 ml of sample, then 1.5 ml of digestion solution and finally 3.5 ml of sulphuric acid solution. Tightly cap the tubes and invert each to mix completely. Digest them at 150^{o}C for 2 hours. Let the samples cool to room temperature and wait to relieve any pressure generated during digestion and then colorimetric determined on the Hach DR-2000 spectrophotometer at selected wavelength. The method was used within the range 0 - 900 mg/l. *(Based on the Standard method by Clesceri and al., 1998)*

N.B: The solution should be prepared with high precaution. Add them slowly to the vials in order to avoid spills.

2.3.Design parameters determination

Over several cycles, there was done frequent sampling and analysis of OUR, TOC and SS in order to produce growth curves of the batch reactor according to the classical batch growth curve (Bitton, 2005). During the initial phase, the growth is at its maximum (C>> Ks ➔ $\mu = \mu_{max}$) and the yield is close to the true yield ($Y = \Delta X/\Delta C$). During the decay phase $\Delta X = -k_d.X$.

In addition to the growth curves, OUR results will be used for COD fractionation and maximum growth rate determination. Three methods can be used for determining influent COD fractions (RBCOD) according to Ekama and al. (1986): the flow-through activated sludge system method, Aerobic batch reactor method, and the anoxic batch reactor method. Only the two latter methods allow the calculation of the maximum specific growth rate (μ_{max}) of the heterotrophic organisms.

Digestion test by aerating the sludge over longer time without adding new wastewater was also done for the determination of decay rate (k_d).

a. The readily biodegradable COD concentration or fraction

The influent RBCOD concentration is given by the following formula:

$$\frac{dO}{dt} = (1 - Y)\frac{dC}{dt}$$

$$dC = \frac{{}^{dO}/_{dt}}{1 - Y}.dt$$

$$dC = \frac{OUR.t}{1 - Y}.\frac{V_{ml} + V_{ww}}{V_{ww}}$$

$$\boldsymbol{RBCOD_{in} = \frac{1}{1 - f_{cv}.Y_h}.\Delta O.\frac{V_{ml} + V_{ww}}{V_{ww}}}$$

Where:

1/ $(1 - f_{cv}.Y_h)$: mgCOD consumed per mgO utilized = 3 (for Y_h = 0.45 mgVSS/mgCOD and f_{cv} = 1.42 mgCOD/mgVSS)

Vml: volume of mixed liquor (at concentration Xv mgVSS/l) (l)

Vww: volume of wastewater (l)

ΔO: mass of oxygen utilized in RBCOD consumption per litre batch mixture (OUR*t) (mgO/l)

And the RBCOD fraction with respect to total COD is given by:

$$\boldsymbol{f_{ts} = \frac{RBCOD_{in}}{COD_{tot}}}$$

b. Maximum specific growth rate of the heterotrophs

According to Monod kinetic, growth rate is a function of limiting substrate such as organic substrate (C_S), oxygen (O_2) or ammonia (N):

$$\mu = \mu_{max}\left(\frac{C_s}{K_s + C_s}\right)\left(\frac{C_{O_2}}{K_{O_2} + C_{O_2}}\right)\left(\frac{C_N}{K_N + C_N}\right)$$

K_{O2} *and* K_N are both lower than 1 mg/l, while it often is much higher concentrations in a bioreactor (C >> K). The saturation of these compounds $\left(\frac{C}{K+C}\right)$ will thus be close to 1 and

do not appear in the rate expression. Thus, the growth rate is described with respect to organic substrate only.

$$\mu = \mu_{max}\left(\frac{C_s}{K_s + C_s}\right)$$

The growth rate is proportional to the concentration of organisms X_H:

$$\frac{dX_H}{dt} = \mu X_H = \mu_{max}\left(\frac{C_s}{K_s + C_s}\right)X_H$$

Consumption of substrate is proportional with the growth rate with the growth yield as ($Y_{X/S}$) as proportionality constant.

$$\frac{dX_H}{dt} = Y_{X/S}\frac{dC_S}{dt} \quad \rightarrow \frac{dC_S}{dt} = \frac{\frac{dX_H}{dt}}{Y_{X/S}} = \frac{\mu X_H}{Y_{X/S}} = \frac{\mu_{max}}{Y_{X/S}}\left(\frac{C_s}{K_s + C_s}\right)X_H$$

Consumption of oxygen (OUR) is proportional with the growth rate and corresponds to the difference between substrate consumed (dC_S) and biomass synthesis (dX), corresponding to ($1 - Y_{X/S}$).

NB: X_H and $Y_{X/S}$ must be expressed as oxygen equivalents (COD) in order to have matching units.

$$\frac{dO}{dt} = \left(1 - Y_{X/S}.f_{cv}\right)\frac{dC_S}{dt} = \left(1 - Y_{X/S}.f_{cv}\right)\frac{\frac{dX_H}{dt}}{Y_{X/S}} = \frac{\left(1 - Y_{\frac{X}{S}}.f_{cv}\right)}{Y_{X/S}}\frac{dX_H}{dt}$$

$$\frac{dO}{dt} = \frac{\left(1 - Y_{X/S}.f_{cv}\right)}{Y_{X/S}}\mu X_H = \frac{\left(1 - Y_{X/S}.f_{cv}\right)}{Y_{X/S}}\mu_{max}\left(\frac{C_s}{K_s + C_s}\right)X_H$$

In the beginning of a batch cycle, the substrate concentration is normally high so $C_S >> K_S$ resulting in that $\mu = \mu_{max}$ and give the following expression (dO/dt = OUR):

$$\frac{dO}{dt} = \frac{\left(1 - Y_{X/S} \cdot f_{cv}\right)}{Y_{X/S}} \mu_{max} \cdot X_H = OUR$$

$$\boldsymbol{\mu_{max} = \frac{OUR \cdot Y_{X/S} \cdot 24}{\left(1 - Y_{X/S} \cdot f_{cv}\right) \cdot X_H}}$$

c. The decay rate

The reactors were left without feed for more than ten days. OUR and VSS were measured every day. The slope issued from the plot of logarithm of OUR values over time (in days) will give the decay rate of heterotrophs in the reactor.

The rate of active mass loss is expressed with a 1st order rate:

$$\frac{dX}{dt} = -k_d \cdot X_a$$

Where:

k_d: Decay rate (d^{-1})
X_a: Concentration of active mass ($gCOD/m^3$)

A fraction of the decaying mass is non-biodegradable and accumulates in the system as a particulate endogenous residue (X_e), which then becomes a part of the VSS. Generation of endogenous residue is proportional to the decay rate and the non-biodegradable fraction (f) of the decaying mass:

$$\frac{dX_e}{dt} = -f\frac{dX}{dt} = f \cdot k_d \cdot X$$

Where:

f: Fraction of active mass that is non-biodegradable (-)
X_e: Concentration of endogenous residue ($gCOD/m^3$)

The rate of oxygen utilisation due to consumption of dead mass is proportional to the decay rate and the biodegradable fraction of the active mass (*1 – f*).

$$\frac{dO}{dt} = -(1-f)\frac{dX_a}{dt} = (1-f)k_d \cdot X_a$$

Rearranging the expression for oxygen consumption the decay rate is determined graphically:

$$\ln OUR_1 = \ln OUR_0 - k_d \cdot 1$$

3. Results and Discussion

3.1.Environmental factors

The operational conditions in the tests are shown in figure 8 to 10.

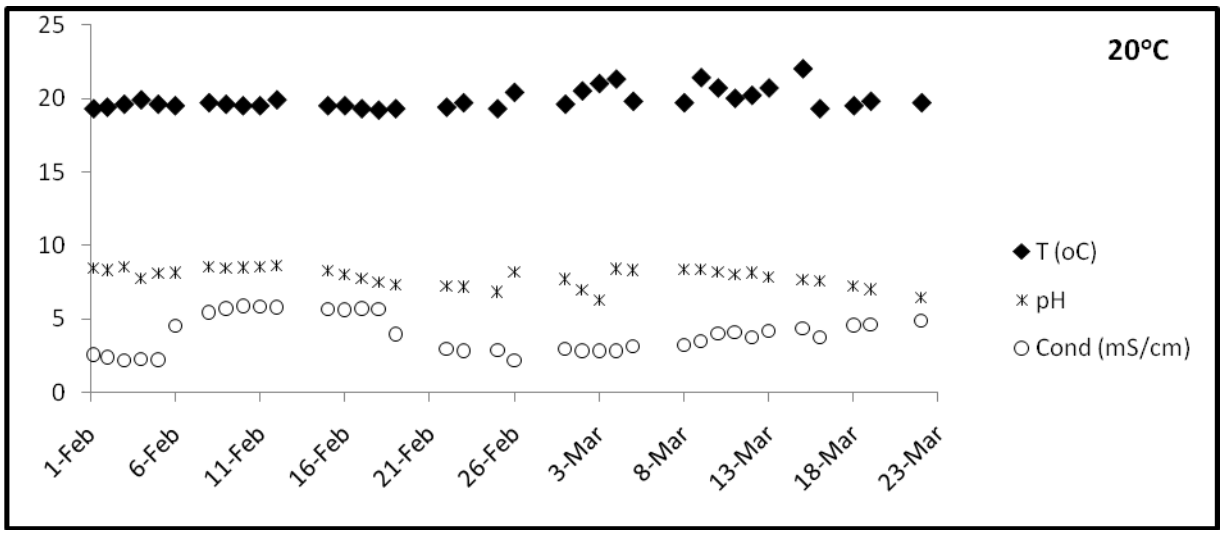

Figure 8: Environmental factor for reactor 1

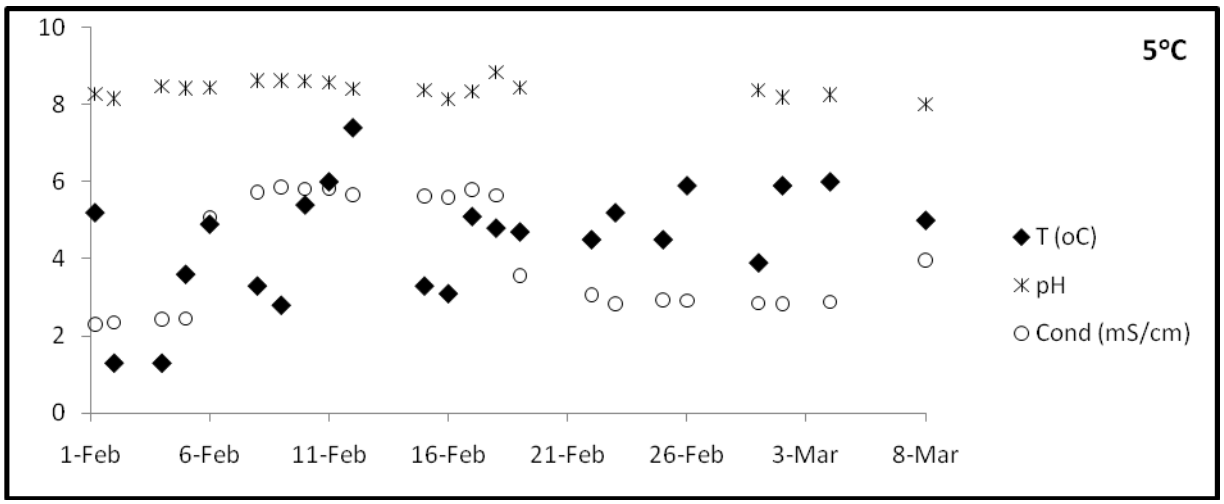

Figure 9: Environmental factor for reactor 2

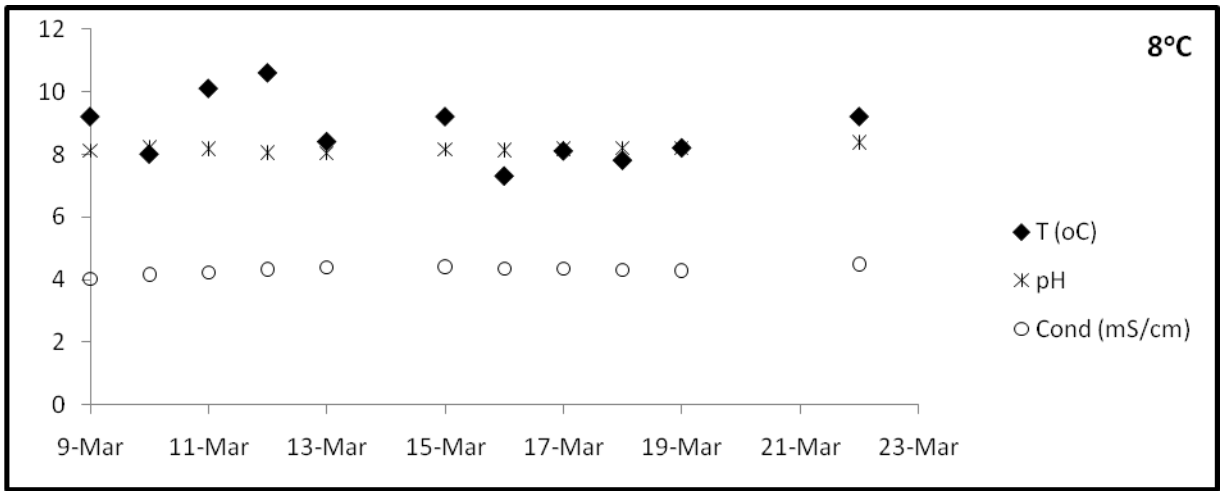

Figure 10: Environmental factor for reactor 3

The three figures above show the life condition of microorganisms, in each reactor, during the experiment.

a. Temperature

For reactor 1, the temperature did not change that much and from February 2nd and March 23rd, we recorded a minimum temperature of 19.2°C and a maximum of 21.4°C. It is close to 20°C.

For reactor 2, the target temperature was 5°C and the recorded temperature varied from 1.3°C to 7.4°C. Since this experiment was done inside the cold room at UIS chem.-lab, it was hard to keep the temperature constant. The room is temperature-sensitive, so a frequent entrance and exit of the room was enough to trigger an increase in temperature. The lower temperature can be explained by the fact that this cold-room is used as storage for chemicals, so basically they change the room temperature, as they wanted.

For reactor 3, the temperature was relatively constant during the experiment.

The aim of these three experiments was to see the temperature effect on the growth of microorganisms. As Sperling (2007) stipulate, *the temperature has a great influence on the microbial metabolism, thereby affecting the oxidation rates for the carbonaceous and nitrogenous matters*. The relation between temperature and reaction coefficient can be expressed by the following equation:

$$\mu_{maxT} = \mu_{max20} \cdot \Theta^{(T-20)}$$

Where

μmax_T: maximum growth rate at a temperature T (d^{-1})
μmax_{20}: maximum growth rate at a standard temperature of 20°C (d^{-1})
Θ: Temperature coefficient (= 1.07)
T: temperature of the medium (°C)

N.B: this equation is only valid in the temperature range from 4 to 30°C.

b. pH

For reactor 2 and 3, the pH values were between 8 and 8.9 during the period of study, while for reactor 1, the pH dropped four times from 8 to around 6 during the experiment. This pH drop might be explained by the nitrification process (oxidation of ammonia to nitrite and then to nitrate), which occur in an activated sludge plants at a certain temperature and sufficient

retention time. At 5 and 8^{o}C, nitrification rarely occurs due to high temperature sensitivity to the nitrifying bacteria (Henze and al., 2002).

c. Conductivity

As you can notice from the figures, the conductivity values were high and variable during the experiment. At the beginning the values were around 2 mS/cm, and then it increased to around 5mS/cm. These values may be explained by that this study was done during the winter period, and during this period of snow road-salt was added to the roads to make it passable. The salt was gradually dissolved and followed surface water into the sewers and mixed with the sewage. The recorded conductivity in this experiment was about ten times higher than in the sewage unaffected by road-salt. High salinity may affect the biological growth.

d. Nutrients

For some reason, the wastewater was found to be deficient in nitrogen and phosphorus so we had to add macronutrients into the bioreactor (see appendix 8). According to Benfield and Randall (1980), BOD_5/N/P ratio should be 100:5:1.

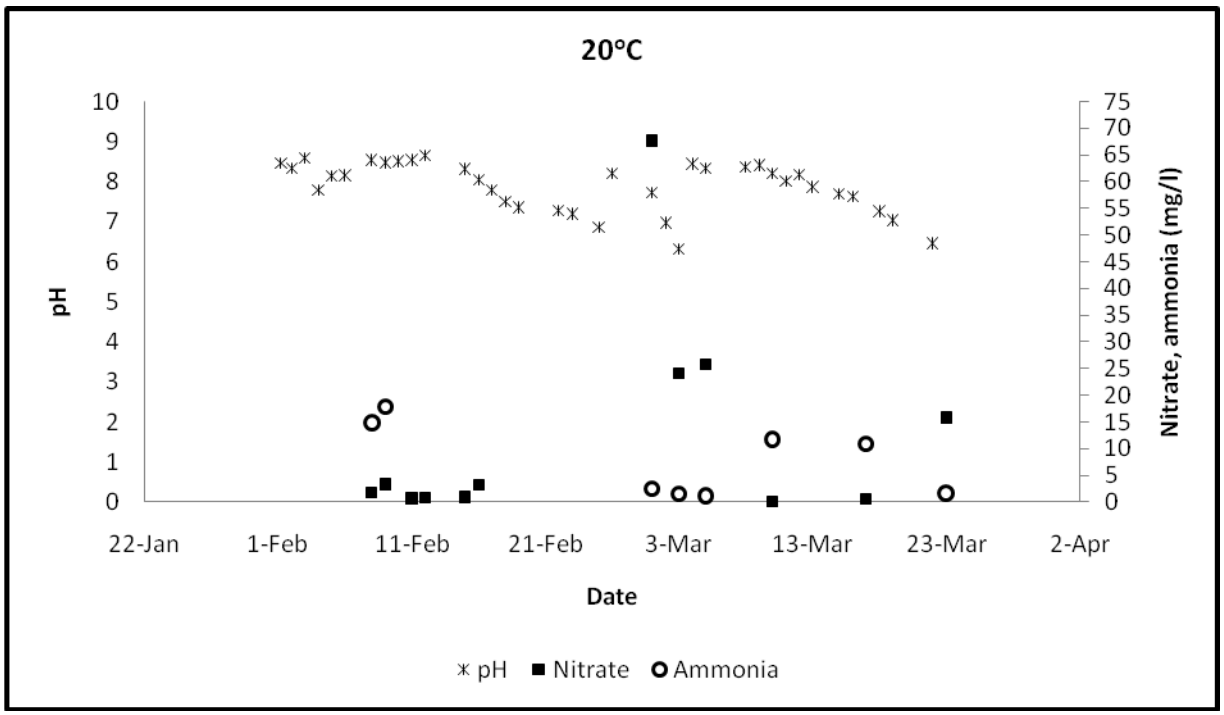

Figure 11: Relation between pH, nitrate and ammonia (Reactor 1)

pH, nitrate and ammonia concentration are correlated as shown in figure 11. From 15th of February, a change in pH was noticed in reactor 1 and it occurred until the end of the

experiment even we compensated the loss by adding carbonates into the reactor. During the period where the pH is low, the concentration of nitrate in the reactor increased, while the ammonium concentration decreased. It can be concluded that nitrification process occurred in reactor 1 resulting in a decrease of the pH values. All the parameters were favorable for the nitrification process to happen; the temperature was high enough (20^{o}C) and we operated with long sludge age. No such process were noticed in reactor 2 and 3, the temperature was too low for the nitrifying bacteria to grow.

e. Organic carbons

The different fractions of the organic carbons were estimated based on measurements (COD, TOC) and calculation from OUR curves. For the calculation, the raw wastewater with total COD of 380 mg/l was chosen (see appendix 1). The calculation of the biodegradable fraction of the substrates gave an average of about 300 mg/l. The analysis of the effluents from TOC measurements came out with an average of 39 mgCOD/l[8] (13 mgTOC/l, see appendix 3), which corresponds to the unbiodegradable soluble substrates. Therefore, the unbiodegradable particulate substrate is equal to 41 mg/l.

As a result, the substrate is composed of 78.95% biodegradable COD, 10.79% of unbiodegradable particulates COD and 10.26 % of unbiodegradable soluble COD.

3.2.Characterization of biomass

a. Bacterial Growth, OUR and TOC curves

During the degradation process, bacteria available in the wastewater will consume the biodegradable part of substrates to form new cells. The growth is at its maximum when the concentration of substrates is higher. It will increase the VSS in the reactor. Then, the growth will be constant as the concentration of substrates gradually decreases. At the end of the process a decrease of substrate concentration and an increase of VSS concentration will be noticed as shown in figure 12 to 14. Oxygen will be consumed during this process, which explains the decrease of OUR curves on the three figures. The activity of microorganisms is higher at high concentration of substrates leading to high OUR and the activity decreases when the available oxygen had been consumed.

[8] COD/TOC ratio = 3

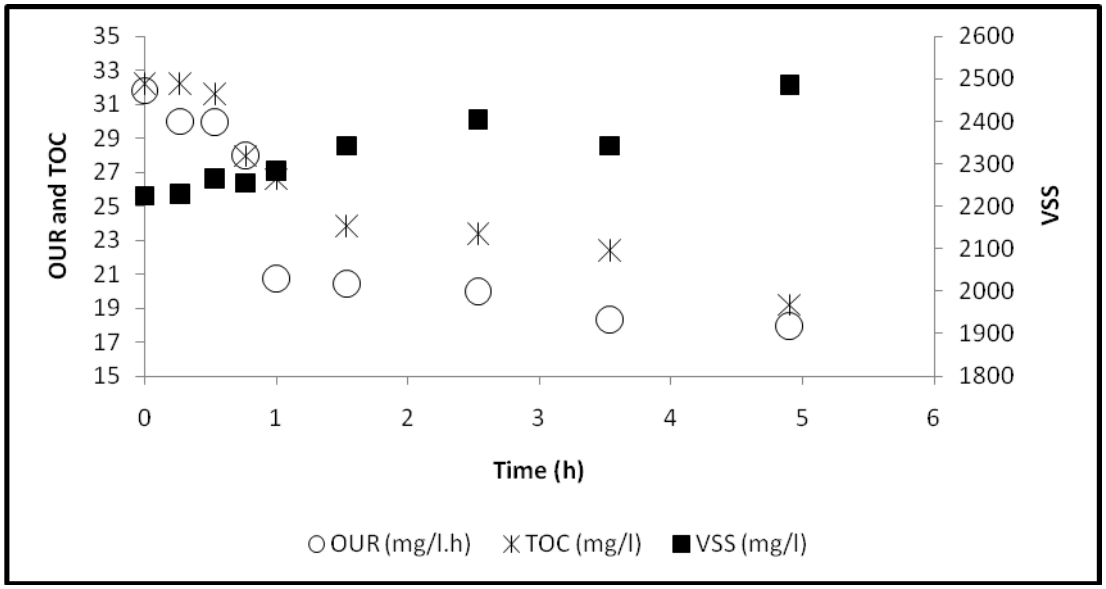

Figure 12: Growth curve for reactor 1 (1 Mar 2010)

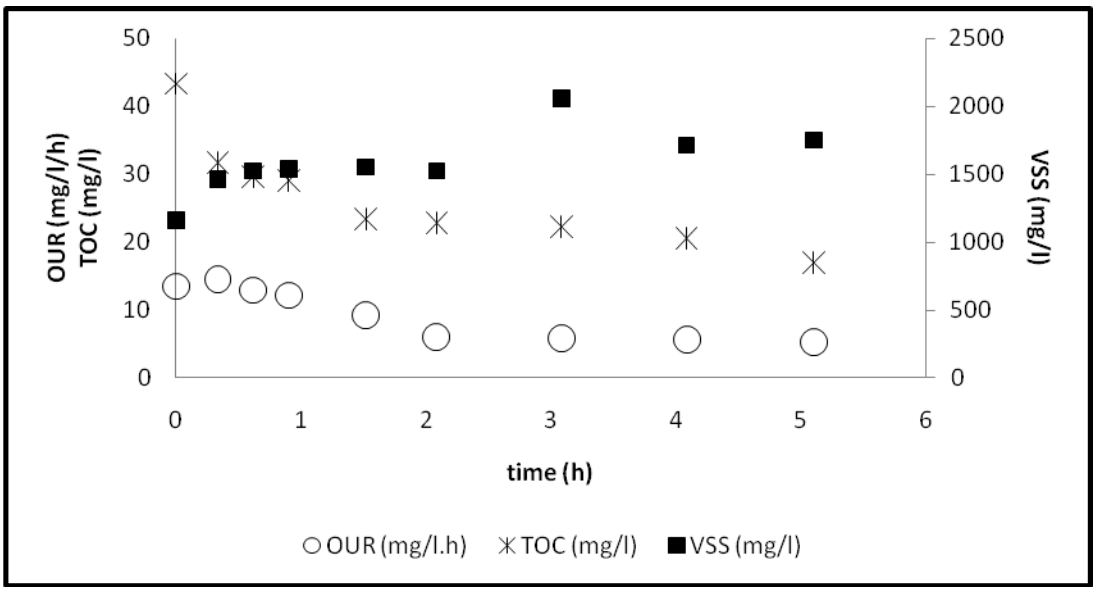

Figure 13: Growth curve for reactor 2 (23 Feb 2010)

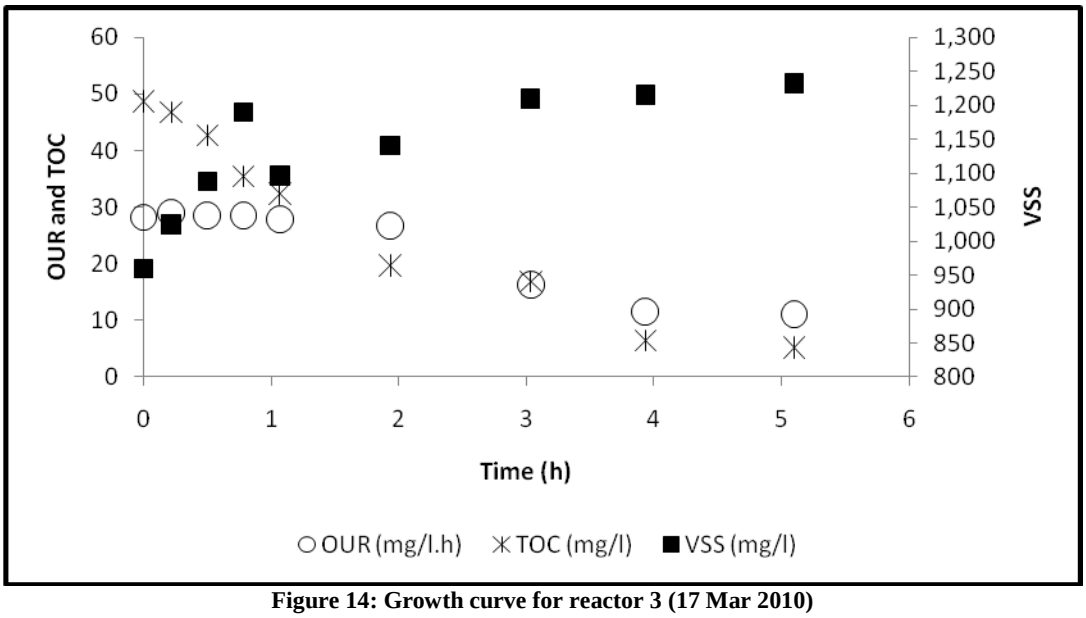

Figure 14: Growth curve for reactor 3 (17 Mar 2010)

b. Decay rate

Based on the digestion curves a decay rate of $0.11d^{-1}$ had been found in the reactor at 20^oC. After temperature correction a value of $0.08\ d^{-1}$ was found for the reactor at 8^oC[9], and $0.07\ d^{-1}$ at 5^oC[10]. The decay rate is a temperature dependant. Its value should be higher at higher temperature and lower at very low temperature. The results had exposed that fact.

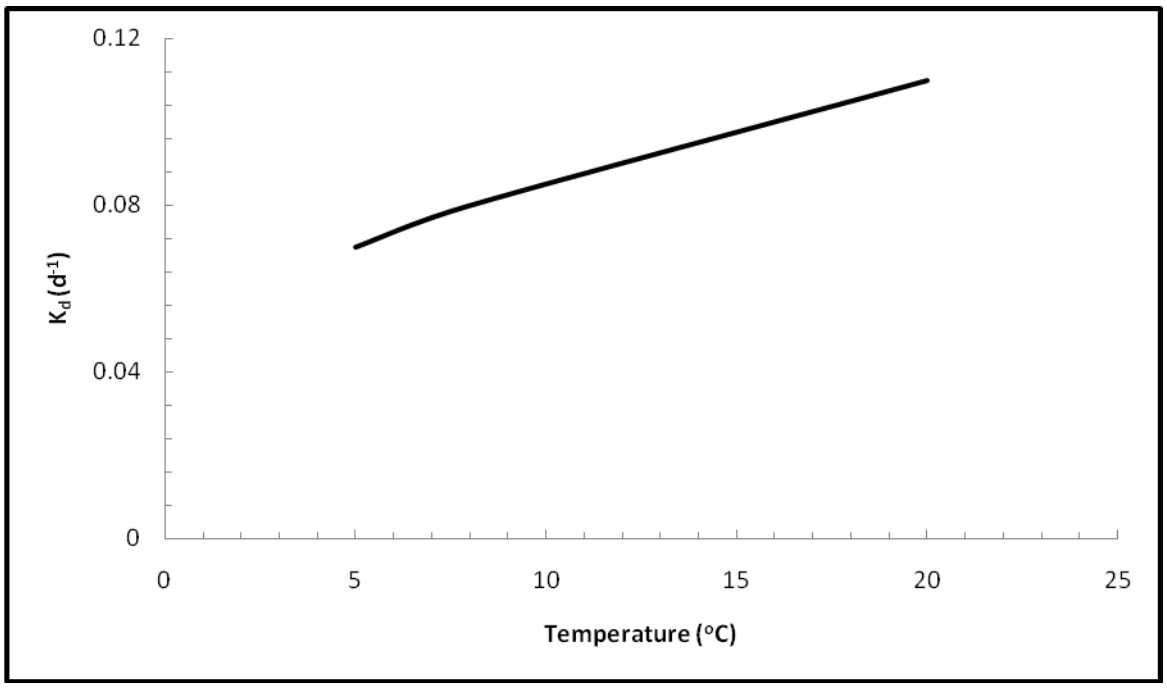

Figure 15: Decay rate as a function of temperature

3.3.Sludge retention time

Sludge retention time is an important factor in the design of biological wastewater treatment plant. The different SRT values obtained during the test are 19.7 days, 9.2 days, and 4.9 days respectively for reactor 1, 2 and 3 (see appendix 4).

According to these results, the SRT in reactor 1 (at 20^oC) is higher than the two other reactors, which were operated at low temperature (5 and 8^oC). This is contradictory to the reality because the SRT should normally be lower at higher temperature. The reason for this difference is that we did not setup a desired SRT value at the beginning of the experiment. SRT was calculated based on the biomass in the reactor and the biomass wasted per day. Almost a same amount of biomass were wasted in the three bioreactors, while it should have been more in reactor 1 because it does not have the same volume as reactor 2 and reactor 3. Hence, SRT values cannot be compared based on temperature, at least between reactor 1 and

[9] $K_d(8^oC) = 0.11 * 1.03^{(8-20)}$

[10] $K_d(5^oC) = 0.11 * 1.03^{(5-20)}$

2 or 3. Comparison can be done between reactor 2 and 3. Both reactors had the same volume, and same amount of solids were wasted each day. The SRT was lower at 8^{o}C with an average of 4.9 days compared to reactor 2 (operated at 5^{o}C), which had an SRT of 9.2 days. Thus, for bioreactors running with the same conditions, except for temperature, SRT values should be lower at high temperature and vice versa.

4. Mathematical modeling

Total influent COD can be subdivided into biodegradable COD and unbiodegradable COD. Bacteria will use the biodegradable COD (BCOD) during the degradation process, but not all BCOD are immediately available for bacterial use. BCOD are composed of readily biodegradable COD (RBCOD) and slowly biodegradable COD (SBCOD). First, Bacteria have to convert SBCOD into RBCOD before using it for growth. Figure 14 summarize the different processes occurring during biological treatment.

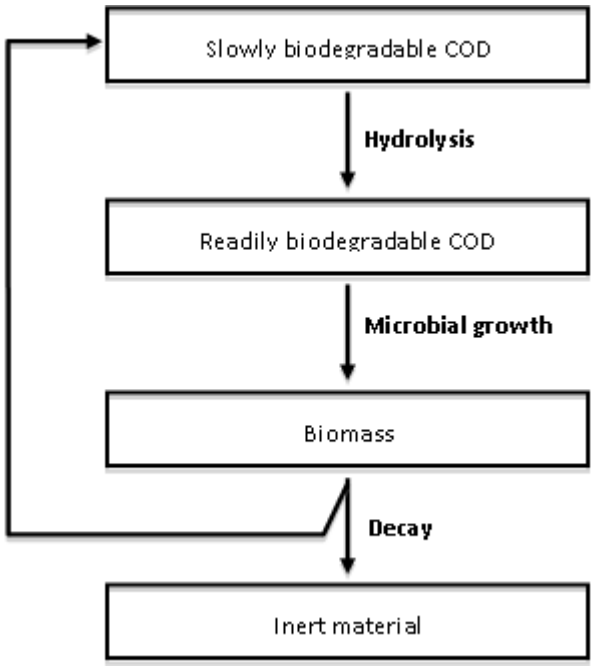

Figure 16: Biological conversion
(Source: adapted from Henze et al, 2002)

Three processes take place during organic carbons removal: Microbial growth, hydrolysis and decay.

4.1.Biological growth

Bacteria in the wastewater are only able to use very small and simply built molecules for growth. The process can be described as follow:

$$r = \mu_{max} \cdot \frac{C_s}{K_s + C_s} X_H$$

where:

r : volumetric biological growth rate (gCOD/l.d)

μ_{max}: maximum specific growth rate (d-1)

Ks: half-saturation constant for RBCOD ($mgCOD_{su}$/l)

Cs: RBCOD (mgCOD/l)

X_H: heterotrophic organisms (mgCOD/l)

4.2. Hydrolysis

Hydrolysis is the conversion of larger molecules (particulate and dissolved solids) into small molecules that can be easily used by bacteria for their growth. This reaction is very slow compared to biological growth processes. Hydrolysis processes can be described with a surface-saturation expression where the substrate/biomass ratio $^{X_s}/_{X_H}$ governs the hydrolysis rate:

$$k_h = k_c \,.X_H \,. \frac{\frac{X_s}{X_H}}{K_x + \frac{X_s}{X_H}}$$

where:

k_h: volumetric hydrolysis rate (gCOD/l.d)

k_c : hydrolysis constant

Kx: half-saturation coefficient for hydrolysis (mgCOD/mgCOD)

4.3. Decay

Decay is the decomposition of dead microorganisms into small matter. It is also known as lysis, endogenous respiration or maintenance. Sometimes decay includes also predation occurring in the reactor or grazing. Decay is described as a first order process with regards to biomass.

$$\mathbf{r_d = k_{dH} \,.\, X_H}$$

where

k_{dH}: decay rate for heterotrophic organisms (d-1)

r_d: volumetric decay rate(gCOD/l.d)

All these processes can be summarized as presented in table 7.

Table 7: Process kinetics and Stoichiometry for aerobic carbon removal

Component / Process	Ss	So	X_H	Xs	X_E	Rate equation (gCOD/l.d)
Growth of heterotrophs	$\frac{-1}{Y_H}$	$\frac{-(1-Y_H)}{Y_H}$	1			$\mu_{max} \cdot \frac{S_s}{K_s + S_s} X_H$
Hydrolysis of SBCOD	1			-1		$k_c \cdot X_H \cdot \frac{\frac{X_s}{X_H}}{K_x + \frac{X_s}{X_H}}$
Decay of heterotrophs		$(1- f_d)$	-1		f_d	$\mathbf{k_{dH} \cdot X_H}$

The rate equation multiplied with the stoichiometry factor yields the effects the rate have on each state variable.

4.4. Simulation with AQUASIM

AQUASIM is a computerized program designed for the identification and simulation of aquatic system in laboratory, in technical plant and in nature (Reichert, 1998). The main function of AQUASIM is to perform model simulation by comparing measured results with the model calculation. This program allows, also estimation of certain parameters such as maximum specific growth rate, rate of hydrolysis, decay rate based on the measured data.

a. Input data

The values in the table 8 and 9 were used for the simulation of the three reactors in AQUASIM. The sludge retention time was respectively 19.7 days, 9.2 days and 5 days for reactor 1, reactor 2 and reactor 3.

Table 8: Compounds in the aerobic carbon removal model

		Value		
Description	Unit	20°C	5°C	8°C
Dissolved compounds				
RBCOD	mgCOD/l	50	50	50
Dissolved oxygen	mgO/l	>7	>7	>7
Particulate compounds				
Heterotrophic organisms	mgCOD/l	1159	1043	666
SBCOD	mgCOD/l	250	250	250
Inert residue from dead cells	mgCOD/l	502	134	53
Inert particulate COD from influent	mgCOD/l	699	326	178

Table 9: Parameters in the aerobic carbon removal model

Description	Unit	20°C	5°C	8°C
Stoichiometric parameters				
Growth yield for aerobic heterotrophic organisms	mgCOD/mgCOD	0.66	0.66	0.66
Unbiodegradable residue in cells	mgCOD/mgCOD	0.20	0.20	0.20
Kinetic parameters				
Maximum specific growth rate for heterotrophic organisms	d^{-1}	1.86	0.68	2.52
Hydrolysis rate	d^{-1}	1.47	0.26	2.37
Decay rate for heterotrophic organisms	d^{-1}	0.11	0.07	0.08
Half-saturation coefficient for RBCOD	$mgCOD_{Su}/l$	10	10	10
Half-saturation coefficient for hydrolysis compounds	mgCOD/mgCOD	0.027	0.027	0.027

b. Simulation Output

Figure 17 to 19 illustrate the simulation output from AQUASIM software. The program compares the experimental data with the model for estimation of model parameters. These three figures show how close should be the measured OUR and the calculated OUR (model) curve if the experiment goes as expected.

As example, figure 17 shows clearly the consumption of the different fraction of substrates in the wastewater: the first peak correspond to the degradation of the readily biodegradable substrates and the second peak matches for the consumption of the slowly biodegradable substrates.

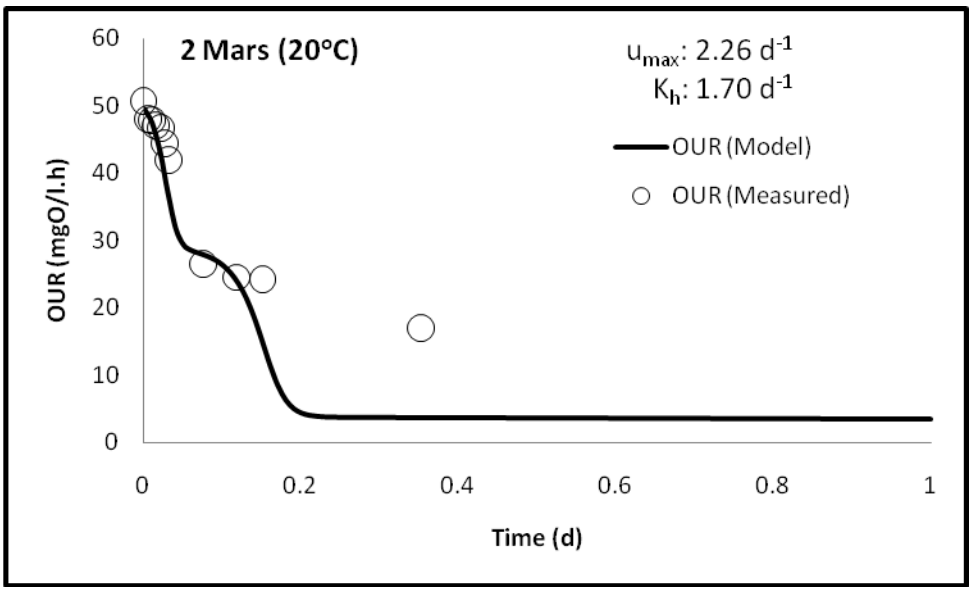

Figure 17: Comparison of OUR measured with the Model (reactor 1)

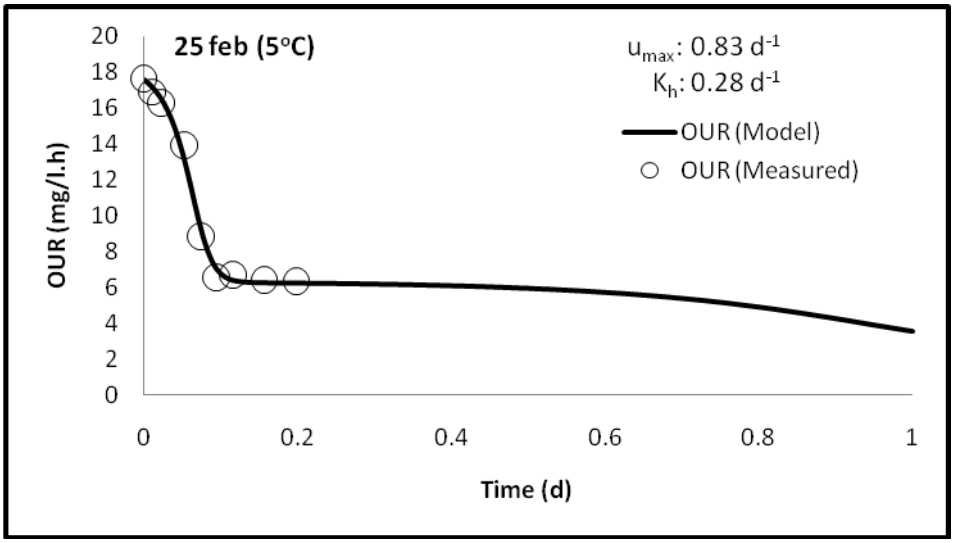

Figure 18: Comparison of OUR measured with the Model (reactor 2)

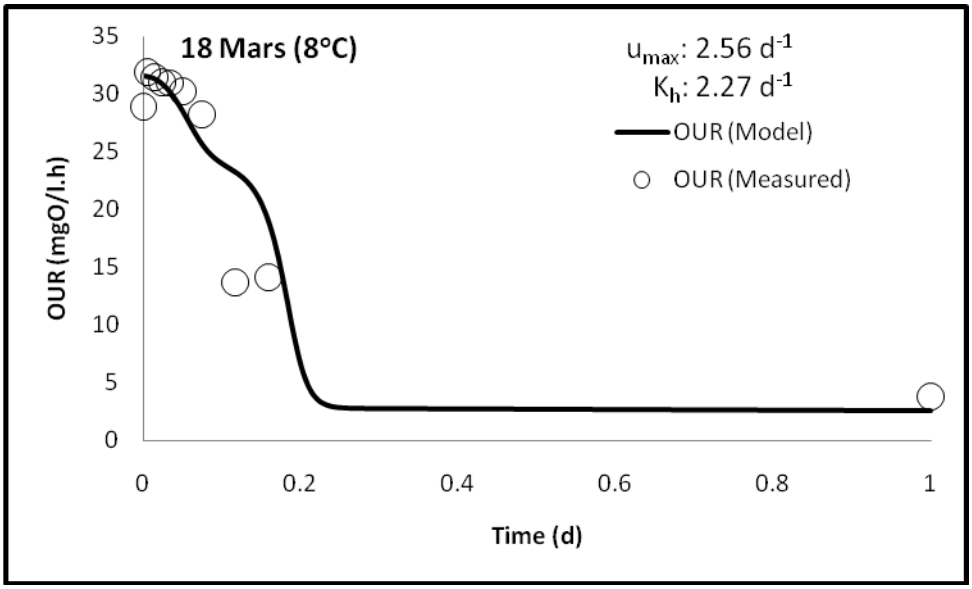

Figure 19: Comparison of OUR measured with the Model (reactor 3)

c. Estimated parameters

Parameters such as maximum specific growth rate (μ_{max}) and hydrolysis rate (k_h) were estimated from AQUASIM.

Table 10: µmax and K_h results

	Reactor 1 (20°C)		**Reactor 2 (5°C)**		**Reactor 3 (8°C)**	
parameters	Peak	Average	Peak	Average	Peak	Average
μ_{max}	1.57 – 2.26	1.86	0.57 – 0.83	0.68	2.39 – 2.61	2.52
k_h	1.05 – 0.70	1.47	0.15 – 0.35	0.26	2.27 – 2.46	2.37

According to table 10, the maximum specific growth rates estimated from AQUASIM were 1.86 d^{-1} for reactor 1(20°C), 0.68 d^{-1} for reactor 2 (5°C) and 2.52 d^{-1} for reactor 3 (8°C). Similar to the decay rate, the maximum specific growth rate is temperature dependant, the higher the temperature, the higher the maximum specific growth rate. The results do not concord with the reality since the reactor operated at 8°C had the higher maximum specific growth rate while it should be the reactor 1. The results from reactor 3 appear suspicious. All literatures about wastewater treatment confirm the temperature dependency of μ_{max}. The period of test was only one week for reactor 3 while the others took more than five weeks. A longer test is necessary for reactor 3 in order to compare the results with reactor 1 and reactor 2. Therefore, we conclude that the maximum specific growth rate at 8°C is unreliable. In addition, by using the μ_{max} value obtained in reactor 1 for the temperature correction, we got a μ_{max} value of 0.67 d^{-1} at 5°C[11], which is very close compared with what we got during the parameter estimation (0.68 d^{-1}), and 0.82 d^{-1} at 8°C[12], which is more realistic.

For some reasons that I could not explain, the difference between μ_{max} values for the three measurements is very significant. The same conditions were applied for the simulation; consequently the μ_{max} values should be similar or close. The same problem happens for the hydrolysis rate.

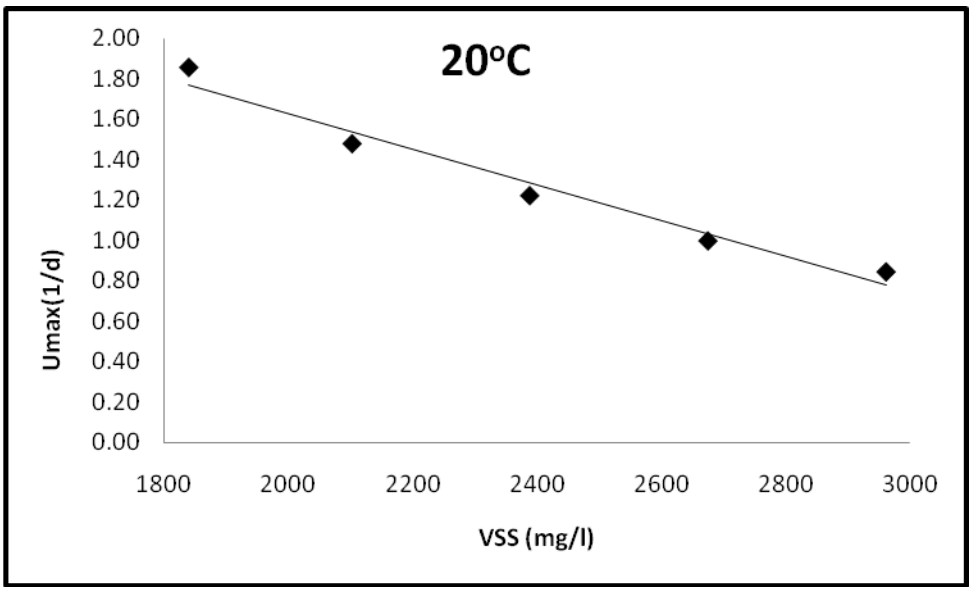

Figure 20: µmax as a function of VSS (reactor 1)

[11] $\mu_{max}(5°C) = 1.86 * 1.07^{(5-20)} = 0.67\ d^{-1}$

[12] $\mu_{max}(8°C) = 1.86 * 1.07^{(8-20)} = 0.82\ d^{-1}$

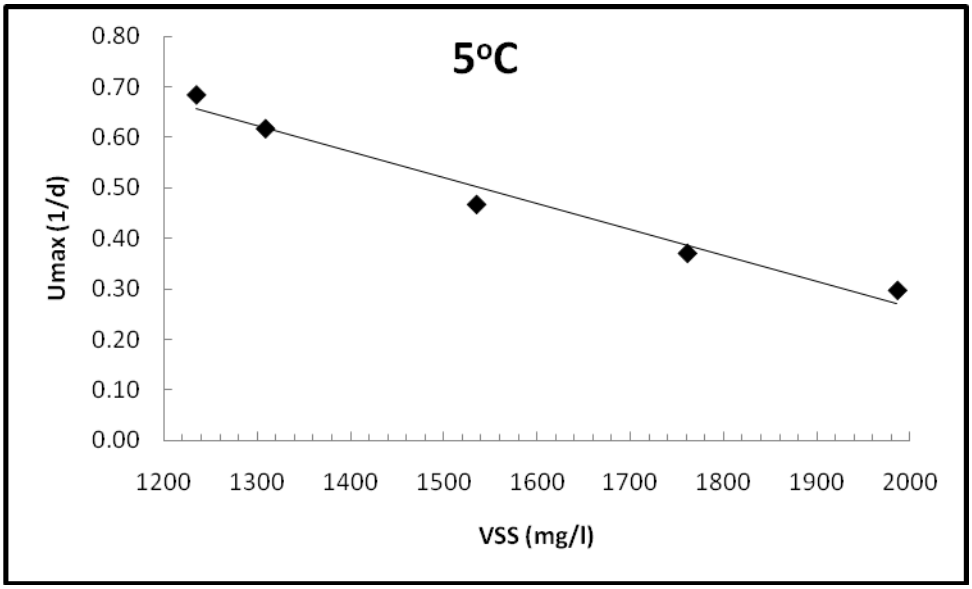

Figure 21: µmax as a function of VSS (reactor 2)

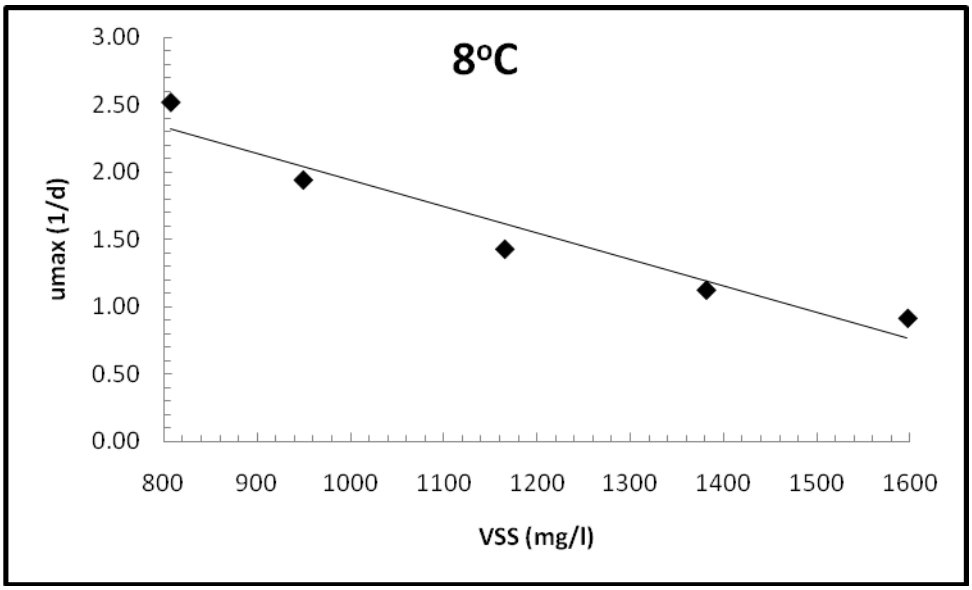

Figure 22: µmax as a function of VSS (reactor 3)

What we experienced during the simulation was that μ_{max} and k_h react by changing the initial biomass concentration in the reactor. Five simulations were performed for each reactor, with five different initial biomass concentrations (see figure 20 to 22 and appendix 5). As a result, we found out that μ_{max} and k_h were lower when the initial biomass concentration was higher. We can conclude that the maximum specific growth rate and the hydrolysis rate decrease as the initial biomass concentration increase. Therefore, it is very important to define the right initial biomass corresponding to the experiment for the simulation with AQUASIM otherwise the parameters such as μ_{max} and k_h might be underestimated or overestimated.

5. Plant design

Two alternatives are available to SNJ concerning the treatment of wastewater by biological means. The first one is a full transformation of the existing plant to biological treatment. The second option is to keep the chemical treatment and use it a pretreatment process and add the new bioreactor for the removal of the remaining BOD.

5.1.Alternative 1: Fully Biological treatment

a. Activated sludge design

Based on the experiment data, simulation with AQUASIM and some information from SNJ the following design parameters could be extracted for the design of an activated sludge plant. This plant is operated at 5oC.

Table 11: Parameters for design

Q	328800.00	m3/d
load	60000.00	kgCOD/d
TOT_{COD}[13]	182.48	mgCOD/l
COD_b[10]	144.07	mgCOD/l
COD_{up}[10]	19.69	mgCOD/l
COD_{us}[14]	18.72	mgCOD/l
MLVSS/MLSS	0.80	
μ_{max}	0.68	d^{-1}
K_s	10.00	mgCOD/l
K_d	0.07	d^{-1}
f_d	0.20	
Y	0.45	gVSS/gCOD
	0.66	gCOD/gCOD)
MLSS	3500.00	mg/l

- *Effluent COD*

The concentration of effluent COD is function of the sludge retention time as shown in figure 23.

[13] TOT_{COD}= load *1000/ Q (mg/l)

[14] Based on the calculation in section 3.1.e, the wastewater from SNJ was composed of 78.95% biodegradable COD, 10.79% of unbiodegradable particulate COD and 10.26% unbiodegradable soluble COD. These fractionations of COD were used to obtain the different COD values in Table 11.

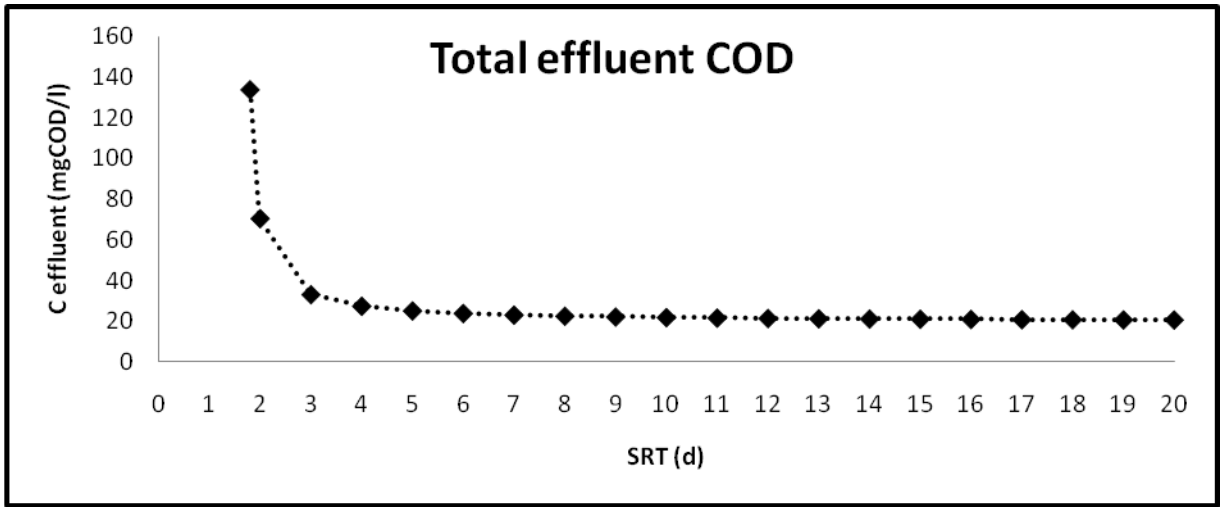

Figure 23: Total effluent substrate concentration as a function of SRT

Sufficient SRT is required in order to achieve certain treatment efficiency. Figure 23 shows that after three days about 35 mg /l of unbiodegradable soluble COD are left in the reactor. That means, the concentration of unbiodegradable particulates COD in the effluent should not exceed 90 mg/l in order to meet the requirement 125 mg COD/l. Therefore, the treatment of the wastewater can be achieved in three days but for a security reason, it is important to use a safety factor. A SRT of 4 or 5 days is reasonable in our case because beyond that the effluent COD remains constant. Continuing the treatment after five days is just a waste of time and waste of money. A bigger volume is required as the SRT increase (see figure 24) and we want to keep the volume as small as possible.

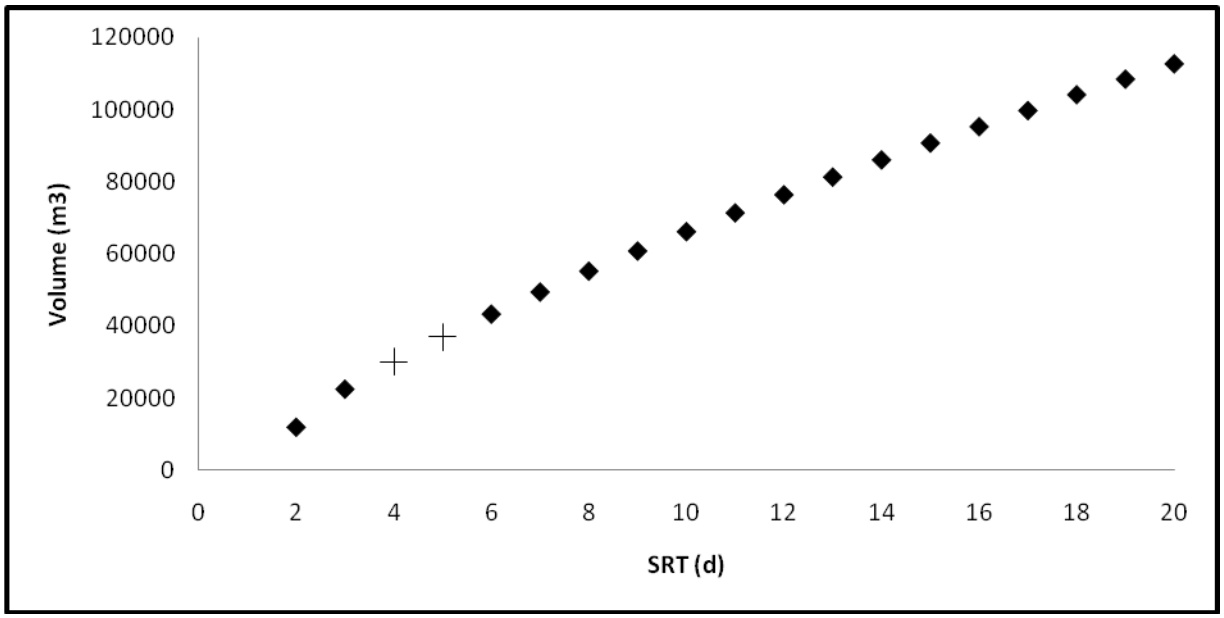

Figure 24: Reactor volume as a function of SRT

So if we choose an SRT of 4 days a reactor with a volume of 30 086 m^3 is required for the treatment. And for a sludge age of 5 days we need a volume of 36 932 m^3. Only with these two values we can see how big the change in volume for one day difference in sludge age is. By changing the SRT for one day, 7000 m^3 extra space is required. Hence, it is important to choose the right SRT for the treatment because the whole process depends on it.

- *Sludge production*

SNJ has an anaerobic treatment plant which converts the sludge into biogas. The more the sludge produced during the treatment, the more the energy produced (biogas). The high production of sludge occurs between 3 to 5 days, about 26 tons of sludge is produced, and then it decrease gradually (see figure 25). Subsequently, our choice for a sludge age of 4 to 5 days is verified. The concentration of COD in the effluent meets the requirement and a high amount of biogas is produced from the sludge.

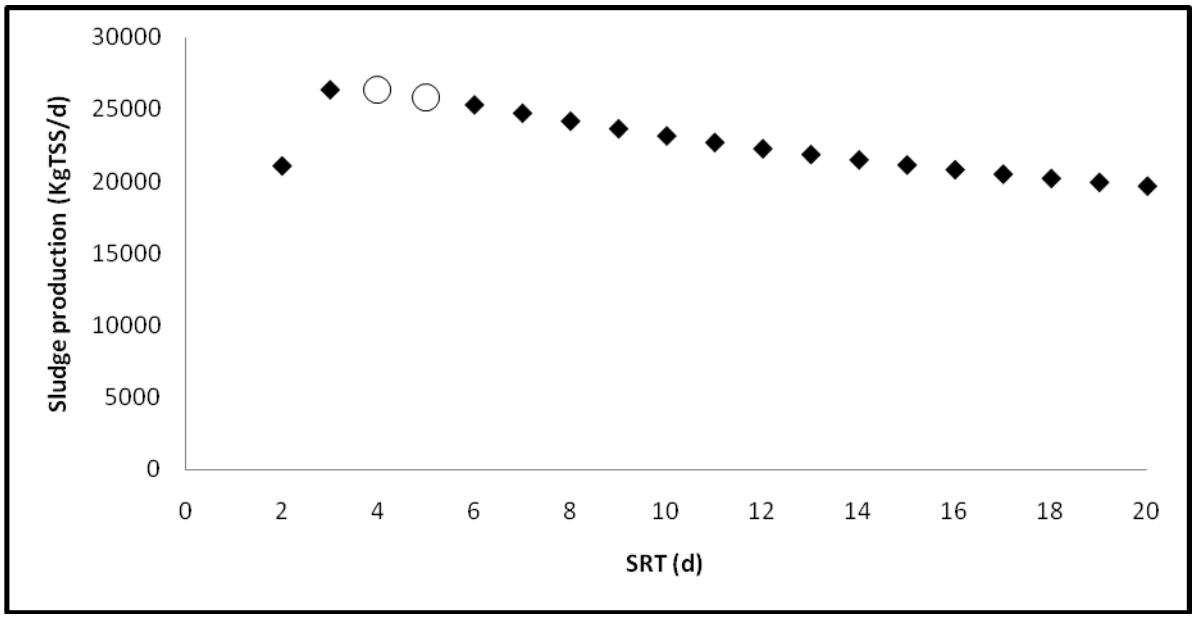

Figure 25: Sludge production as a function of SRT

- *Oxygen consumption*

The oxygen consumed for the growth of microorganisms is very important during the exponential phase and then it becomes constant during the stationary phase. While the oxygen required for endogenous respiration always increase (see figure 26). That can be explained by the fact, the longer the SRT is, the more the amount of dead organisms in the reactor and the more the oxygen required for the degradation of those organisms.

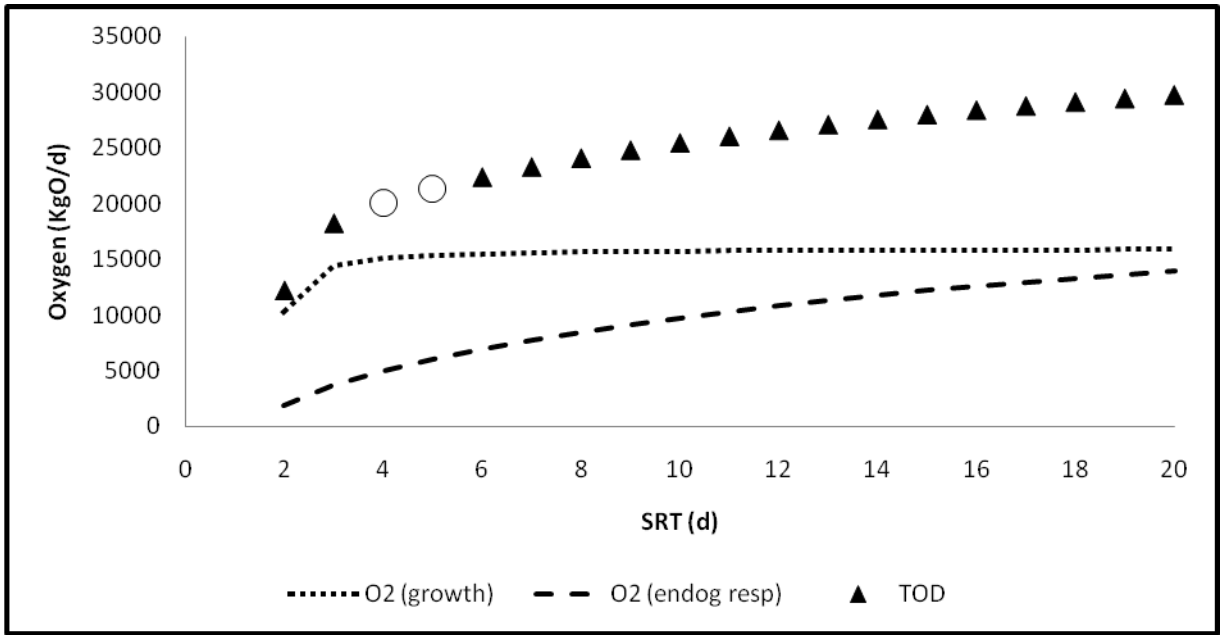

Figure 26: oxygen consumption as a function of SRT

In sum, long SRT leads to a high consumption in oxygen.

b. Aerobic Biofilm reactors design

Several biofilm systems were compared for this design. Table gives the design criteria for each of them.

Table 12: Design criteria for aerobic biofilm reactors

	Trickling filter	**RBCs**	**MBBR**	**Biofilters**
Surface area (m^2/m^3)	45 - 150	200	300 - 800	700 – 900
L_v ($KgBOD/m^3.d$)	0.07 – 3.2	0.8 - 2	4 - 7	3.5 – 4.5
L_A ($gBOD/m^2.d$)		4 - 10	13 - 24	5 – 6.5
COD load ($KgCOD/m^3$)		0.137		
Q		328 800		
BOD/COD ratio		2		

- *Volume of the packing medium*

By adopting the right volumetric organic loading rate, we could estimate the required packing media volume (see table 13).

$$V = \frac{Q \times S_0}{L_v}$$

Table 13: Calculation of packing media volume

	Trickling filter	RBCs	MBBR	Biofilters
L_v (KgBOD/m^3.d)	0.12	0.84	2.39	2.39
V (m^3)	188 477	26 925	9 424	9424

The volume varies from one system to another. Since the calculation is based on the volumetric organic loading rate, the more the system can handle a high organic loading, the less the volume required for packing media is.

- *Surface of the biofilm reactors*

The area of the reactor is given by

$$A = \frac{V}{H}$$

Where:
H: height of the packing medium (m)

By adopting a height of 4 m for the packing medium, the required biofilm reactors surface area is:

Table 14: Calculation of Aerobic biofilm reactor surface area

	Trickling filter	RBCs	MBBR	Biofilters
L_v (KgBOD/m^3.d)	0.12	0.84	2.39	2.39
V (m^3)	188 477	26 925	9 424	9 424
H (m)	4		4	4
A (m2)	47 119		2 356	2 356

c. Design of secondary clarifier

The settling tank can be designed based on the hydraulic loading, which corresponds to the quotient between the influent flow to the plant (Q) and the surface area (A) of the settling tank.

The hydraulic loading is given by the equation

$$L_h = \frac{Q}{A}$$

The settling tank surface area becomes

$$A = \frac{Q}{L_h}$$

The values of hydraulic loading for a specific treatment can be found in many literatures (see table 15).

Table 15: Typical design for secondary clarifiers

Type of treatment	Overflow rate ($m^3/m^2.d$) Average	Peak
Settling following air activated sludge (excluding extended aeration)	16.28 – 32.56	40.70 – 48.84
Settling following oxygen activated sludge	16.28 – 32.56	40.70 – 48.84
Settling following extended aeration	08.14 – 16.28	24.42 – 32.56
Settling following trickling filtration	16.28 - 24.42	40.70 – 48.84
Settling following RBCs:		
Secondary effluent	16.28 – 32.56	40.70 – 48.84
Nitrified effluent	16.28 - 24.42	32.56 – 40.70

Source: adapted from Metcalf and Eddy (2002).

Based on this table, basically the same design value can be used for the activated sludge and the biofilm processes.

With a hydraulic loading rate of 32.56 $m^3/m^2.d$, the required surface area of the secondary settling tank is about 10 101 m^2.

$$A = \frac{328\,880\ m^3/d}{32.56\ m^3/m^2.d}$$

For a settling tank with 4 m depth the required volume becomes 40 404 m^3.

In summary, the total volume[15] required for the treatment will be

Table 16: Volume required for the new plant (alternative 1)

	Activated sludge	**Trickling filter**	**MBBR**	**Biofilters**
Reactor volume (m^3)	36 932	188 477	9 424	9424
Settling tank volume (m^3)	40 404	40 404	40 404	40 404
depth (m)	4	4	4	4
Total volume (m^3)	**77 336**	**228 881**	**49 828**	**49 828**

[15] Total volume: only Bioreactor and secondary clarifier volume. Primary clarifier is not included.

In sum, MBBR or Biofilters technology appears to be the most suitable for SNJ plant based on the volume required. Even the treatment require the same size of settling tank the company can save a lot of space in the reactor by using those technology. The reactor volume is four times less compared to the activated sludge and 20 times less compared to the trickling filter.

5.2.Alternative 2: Chemical treatment and biological treatment

Based on a previous study carried out by Kommedal et al (2008), 74 % of the BOD is removed during the chemical treatment, equivalent to 67 % COD removal. Considering the chemical process as pretreatment, only 26% of the original BOD is then to be treated in the bioreactor.

Using the same calculation as in alternative 1, the results are summarized in table 17.

Table 17: Volume required for the new bioreactor (alternative 2)

	Activated sludge	**Trickling filter**	**RBC**	**MBBR**	**Biofilters**
Reactor volume (m^3)	11 264	62 197	8 885	3 110	3 110
Settling tank volume (m^3)	40 404	40 404	40 404	40 404	40 404
depth (m)	4	4		4	4
Total volume* (m^3)	**51 668**	**102 601**	**49 289**	**43 514**	**43 514**

**Volume of pretreatment basins and primary clarifier are not included

With the new influent COD concentration, the reactor volume required becomes smaller, but the settling tank volume remains the same. Unlike the other treatment systems, which have two clarifiers (primary and secondary), biofilter such as Biofor use the same clarifier for chemical treatment and to settle out sludge flushed out of the reactor (see figure 31).

5.3.Configuration of the new plant

Few configurations can be proposed to SNJ for the future wastewater plant.

a. Configuration 1: Activated sludge

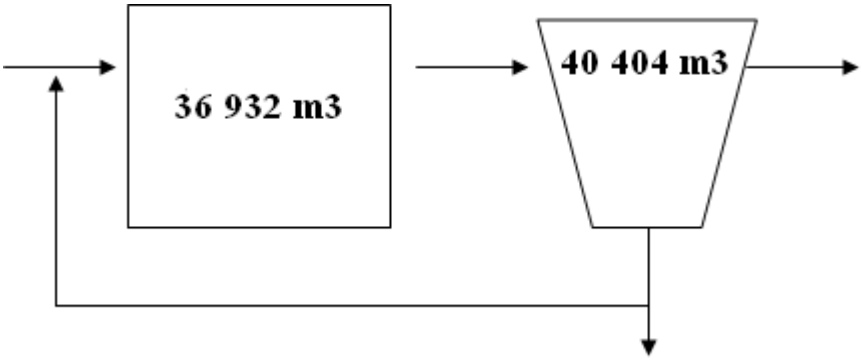

Figure 27: Activated Sludge process

b. Configuration 2: Biofilm process

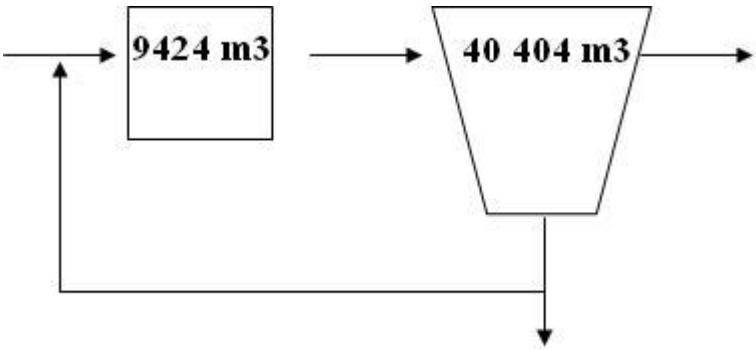

Figure 28: Biofilm process with or without recycle

c. Configuration 3: Chemical treatment and activated sludge

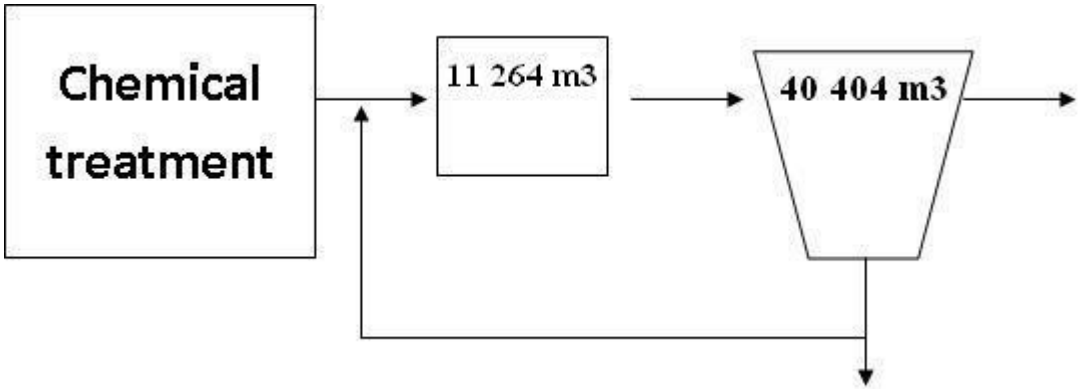

Figure 29: Chemical treatment followed by activated sludge

d. Configuration 4: Chemical treatment and Biofilm process

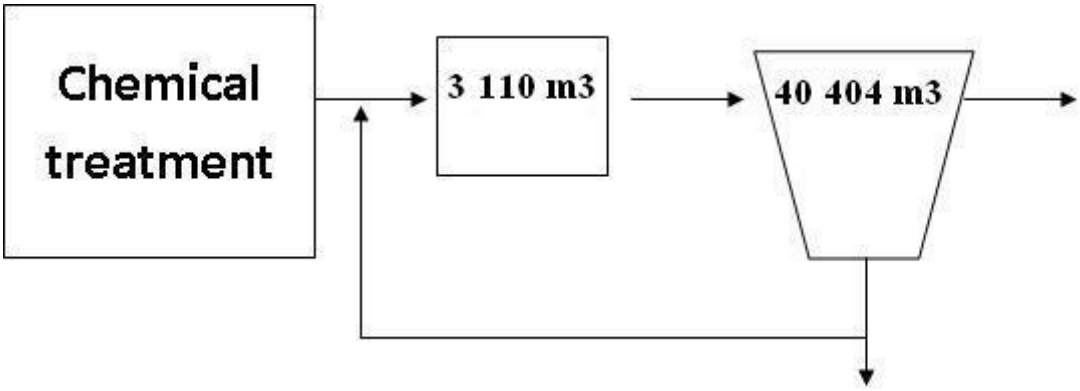

Figure 30: Chemical treatment followed by Biofilm process with or without recycle

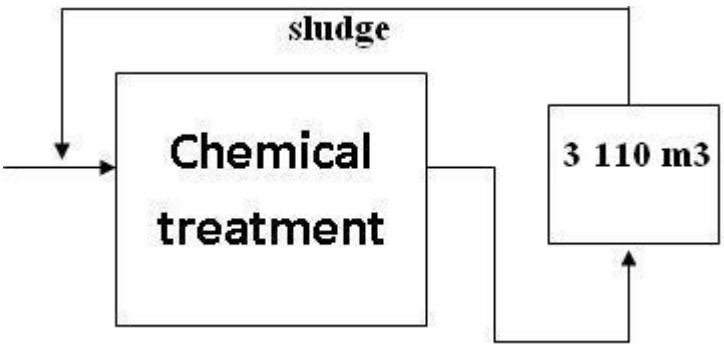

Figure 31: Chemical treatment followed by Biofor process without clarifier

Conclusion

The aim of this project performed from January 2010 until the end of March 2010, was trying to understand the behavior of microorganisms in a specific wastewater and get all the information necessary for the design of a plant based on biological treatment. Three experiments were conducted during the test with the purpose of determining the design parameters such as maximum specific growth rate, decay rate, sludge retention time at different temperature. In addition, the fractionation of the wastewater organic contents was estimated through the OUR, COD, BOD and TOC measurements. Regarding this latter, the wastewater from SNJ was composed of about 78.95% biodegradable substrates, 10.79% unbiodegradable particulate substrates and 10.26% unbiodegradable soluble substrates. The maximum specific growth rate estimated from AQUASIM appeared to be 1.86 d^{-1}, 0.68 d^{-1} and 2.52 d^{-1} respectively for reactor 1 (20^{o}C), reactor 2 (at 5^{o}C) and reactor 3 (8^{o}C); Correspondingly to a decay rate of 0.11 d^{-1}, 0.07 d^{-1} and 0.08 d^{-1}. The maximum specific growth rate was judged too high in reactor 3 because it should be lower than the value found in reactor 1, where the temperature was higher. After temperature correction, a value of 0.82 d^{-1} was found for reactor 3.

By using the parameters obtained in reactor 2 for the design of the new treatment plant, a reactor volume of 36 932m^3 (Activated sludge process), or 188 477m^3 (Trickling filters process), or 9 424m^3 (MBBR or Biofilters) is required for a full transformation of the plant to biological treatment (alternative 1). In case SNJ keep the chemical treatment the new bioreactor volume required is 11 264m^3 if SNJ choose activated sludge, 62 197m^3 if trickling filters is used, and 3 110 m^3 for MBBR or Biofilters (alternative 2). And a secondary settling tank of 40 404m^3 is needed for the sedimentation process. The secondary clarifier can be omitted in the biofilter system following chemical treatment. Diverse biological treatment process designs were presented in this project; it is up to SNJ to choose what suited best for the company.

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	pH	cond	BOD	COD	TSS	VSS	VSS/TSS
1/22/2010	7.36	2.48	86	79	179.17	118.23	65.99
2/5/2010	7.5	5.89	61.4	168	191.24	91.93	48.07
2/18/2010	7.68	2.98	152.8	380	238.18	153.33	64.38

Units:

BOD: mg/l;
COD: mg/l;
TSS: mg/l;
VSS: mg/l;
Conductivity: mS/cm
VSS/TSS: %

Ion chromatography results

	Nitrate mg/l	Phosphate mg/l	Chloride mg/l	Sulphate mg/l	Sodium mg/l	Potassium mg/l	calcium mg/l
2/5/2010	5.53		1480.78	228.07	83.02	2.54	6.44
2/18/2010	0.98	0	661.50	107.34	38.01	1.48	4.56

COD test results

sample	Unfiltered		
1/22/2010	76	82	**79**
2/5/2010	162	178	**168**
	165	167	
2/18/2010	406	448	**377**
	329	323	

8oC			
date	T°C	pH	cond
9-Mar	9.2	8.13	4.03
10-Mar	8	8.23	4.17
11-Mar	10.1	8.19	4.23
12-Mar	10.6	8.06	4.33
13-Mar	8.4	8.05	4.4
15-Mar	9.2	8.16	4.42
16-Mar	7.3	8.15	4.36
17-Mar	8.1	8.19	4.36
18-Mar	7.8	8.2	4.3
19-Mar	8.2	8.2	4.29
22-Mar	9.2	8.39	4.49

5oC			
date	T°C	pH	cond
1-Feb	5.2	8.28	2.3
2-Feb	1.3	8.16	2.35
4-Feb	1.3	8.47	2.44
5-Feb	3.6	8.43	2.45
6-Feb	4.9	8.44	5.09
8-Feb	3.3	8.62	5.73
9-Feb	2.8	8.62	5.86
10-Feb	5.4	8.6	5.82
11-Feb	6	8.57	5.83
12-Feb	7.4	8.41	5.67
15-Feb	3.3	8.38	5.63
16-Feb	3.1	8.14	5.59
17-Feb	5.1	8.35	5.8
18-Feb	4.8	8.85	5.64
19-Feb	4.7	8.45	3.56
22-Feb	4.5	NA	3.06
23-Feb	5.2	NA	2.83
25-Feb	4.5	NA	2.93
26-Feb	5.9	NA	2.91
1-Mar	3.9	8.37	2.85
2-Mar	5.9	8.19	2.83
4-Mar	6	8.26	2.88
8-Mar	5	8.01	3.97

20oC			
date	T°C	pH	cond
1-Feb	19.3	8.46	2.6
2-Feb	19.4	8.33	2.42
3-Feb	19.6	8.58	2.21
4-Feb	19.9	7.78	2.3
5-Feb	19.6	8.13	2.26
6-Feb	19.5	8.16	4.53
8-Feb	19.7	8.54	5.47
9-Feb	19.6	8.48	5.71
10-Feb	19.5	8.51	5.89
11-Feb	19.5	8.54	5.87
12-Feb	19.9	8.66	5.8
15-Feb	19.5	8.32	5.7
16-Feb	19.5	8.05	5.65
17-Feb	19.3	7.79	5.72
18-Feb	19.2	7.51	5.68
19-Feb	19.3	7.36	3.99
22-Feb	19.4	7.27	2.97
23-Feb	19.7	7.2	2.85
25-Feb	19.3	6.86	2.9
26-Feb	20.4	8.2	2.19
1-Mar	19.6	7.73	2.97
2-Mar	20.5	6.97	2.86
3-Mar	21	6.31/7.07	2.87
4-Mar	21.3	6.4/8.44	2.87
5-Mar	19.8	8.33	3.16
8-Mar	19.7	8.36	3.22
9-Mar	21.4	8.41	3.51
10-Mar	20.7	8.2	4.05
11-Mar	20	8.01	4.11
12-Mar	20.2	8.17	3.79
13-Mar	20.7	7.87	4.21
15-Mar	22	7.7	4.4
16-Mar	19.3	7.62	3.78
18-Mar	19.5	7.26	4.6
19-Mar	19.8	7.04	4.65
22-Mar	19.7	6.46/8.2	4.92

Unit : Temperature (°C), Conductivity (mS/cm^2)

Reactor 1 (20oC)

26/2/2010

time (h)	OUR	r2	VSS	TOC
0.00	23.32	1	1722.08	42.52
0.25	22.23	0.9996	1756.40	41.54
0.57	20.78	0.9995	1929.76	36.46
0.87	19.48	0.9996	1945.83	30.26
1.13	18.54	0.9839	1974.80	26.13
1.40	18.52	0.9965	1961.11	22.69
2.35	16.30	0.9982	1981.52	21.16
3.35	16.10	0.9972	2083.23	15.85
4.45	15.22	0.9975	2375.95	12.78

1.3.2010

time (h)	OUR	r2	VSS	TOC
0.00	31.81	0.9995	2224.00	32.24
0.27	29.99	0.9986	2229.04	32.21
0.53	29.98	0.9978	2265.83	31.62
0.77	27.97	0.9998	2255.07	27.95
1.00	20.73	0.9992	2283.70	26.59
1.53	20.46	0.9993	2341.85	23.82
2.53	19.97	0.9998	2403.48	23.4
3.53	18.36	0.9946	2342.38	22.4
4.90	17.97	0.9957	2485.79	19.2
15.93	10.79	0.9994		

2.3.2010

time (h)	OUR	r2	VSS	TOC
0.00	50.69	0.9996	1981.24	43.09
0.13	48.08	0.9992	2296.13	40.37
0.27	47.77	0.9971	2244.27	39.33
0.38	47.02	0.9996	2331.59	37.87
0.52	46.66	0.999	2372.68	27.91
0.63	44.44	0.9985	2254.09	27.05
0.77	41.88	0.9993	2276.13	26.91
1.80	26.46	0.9992	2279.87	23.51
2.82	24.52	0.9996	2233.01	17.87
3.63	24.31	0.9993	2383.24	17.6
8.45	17.00	0.998	2421.13	8.8

3.3.2010

time (h)	OUR	r2	VSS	TOC
0.00	27.85	0.9997	2080.53	48.18
0.25	27.15	0.9996	2105.00	37.38
0.57	27.13	0.9998	2103.82	31.74
0.92	26.84	0.9999	2267.26	29.34
1.17	26.35	0.9997	2266.86	26.10
1.47	26.18	0.9975	2334.72	20.13
1.75	26.03	0.9999	2332.80	18.11
2.32	25.66	0.9998	2306.63	15.90
3.32	22.79	0.9989	2454.28	12.87
4.32	21.84	0.9993	2423.91	5.52

4.3.2010

time (h)	OUR	r2	VSS	TOC
0.00	28.21	0.9991	2023.53	40.26
0.20	27.12	0.9994	2048.57	36.21
0.47	26.59	0.9997	2094.05	31.80
0.72	26.38	0.9995	2159.43	29.40
1.77	25.57	0.9994	2109.33	26.34
2.75	23.55	0.9992	2160.45	25.74
4.25	19.18	0.9954	2139.42	25.38
5.25	19.61	0.9991	2185.44	25.26
6.25	18.22	0.9925	2203.20	13.62
7.25	15.75	0.999	2316.37	11.04

5.3.2010

time (h)	OUR	r2	VSS	TOC
0.00	35.75	1	1705.81	45.22
0.12	35.24	0.9998	1701.89	33.92
0.30	33.35	0.9995	1746.12	24.17
0.72	30.89	0.9942	1768.93	23.59
1.02	22.78	0.9992	1805.26	16.78
1.35	21.73	0.9965	1810.54	16.52
2.10	21.22	0.9944	1814.09	14.97
3.10	21.10	0.9995	1967.42	14.7
4.10	20.48	0.9992	2082.66	13.72

9.3.2010

time (h)	OUR	r2	VSS	TOC
0.00	41.54	0.9994	1839.60	30.54
0.13	40.12	0.9999	1793.27	28.81
0.33	39.76	0.9993	1844.40	26.41
0.57	39.21	0.9995	1875.24	24.53
0.82	37.04	0.9999	1900.20	23.72
1.32	36.38	0.9986	1932.76	19.78
1.82	35.60	0.9832	1939.38	17.70
2.82	33.68	0.9912	1931.57	12.31
3.82	22.58	0.9871	1934.96	11.78
4.82	14.17	0.9967	2031.00	11.71

Reactor 2 (5oC)

16/2/2010				
time (h)	OUR	r2	VSS	TOC
0.00	5.874	0.9978	863.08	29.35
0.27	5.292	0.9881	854.91	25.05
0.65	4.908	0.9993	882.11	20.23
1.27	4.878	0.9962	906.49	19.32
1.93	4.614	0.9984	874.44	18.09
2.97	4.2	0.9985	917.83	17.91
3.93	4.15	0.9976	921.82	17.72
4.93	3.972	0.9973	946.38	16.08
5.93	3.79	0.9957	970.08	13.64
6.78	3.42	0.9935	987.94	10.26

17/2/2010				
time (h)	OUR	r2	VSS	TOC
0.00	4.674	0.9947	750.69	25.3
0.27	3.9	0.9276	731.35	23.07
0.53	3.684	0.9851	775.06	19.09
0.80	3.408	0.9973	783.29	16.87
1.07	3.324	0.9924	795.81	14.9
2.12	3.276	0.9971	807.16	14.05
3.08	3.234	0.997	806.79	12.85
4.05	3.222	0.9953	813.31	12.67
5.38	2.976	0.9916	865.99	9.25

18/2/2010				
time (h)	OUR	r2	VSS	TOC
0.00	9.708	0.9979	654.51	29.59
0.28	10.152	0.9999	679.64	29.41
0.57	9.798	0.9981	700.43	28.7
0.83	8.424	0.9986	710.82	27.6
1.33	5.364	0.9986	712.45	27.4
2.35	4.092	0.9992	724.83	19.99
3.38	3.648	0.9852	726.12	24.87
4.33	2.838	0.993	739.58	19.61
5.33	2.772	0.9909	801.64	17.62

19/2/2010				
time (h)	OUR	r2	VSS	TOC
0.00	11.28	0.9988	727.89	32.84
0.50	10.236	0.9953	676.92	29.21
0.78	9.372	0.9964	804.47	28.39
1.03	9.36	0.9543	821.32	27.88
2.10	5.802	0.9872	849.67	26.66
2.37	4.644	0.9964	870.87	22.31
2.63	4.152	0.9838	864.50	21.61
3.63	4.374	0.9879	890.81	19.82
3.95	4.008	0.9952	893.89	16.68

22/2/2010				
time (h)	OUR	r2	VSS	TOC
0.00	13.176	0.9972	1098.93	59.41
0.27	13.77	0.9882	1101.53	56.69
0.53	12.378	0.9859	1144.38	54.61
0.82	10.89	0.9852	1199.19	44.04
2.28	10.722	0.9955	1187.78	42.47
2.57	10.704	0.9894	1244.12	43.78
3.53	7.836	0.9968	1284.29	37.35
4.40	8.418	0.9911	1258.21	30.67
4.90	6.654	0.9939	1370.21	30.48

23/2/2010				
time (h)	OUR	r2	VSS	TOC
0.00	13.482	0.9998	1161.82	43.32
0.33	14.568	0.9991	1463.32	31.66
0.62	12.936	0.9995	1524.87	29.68
0.90	12.18	0.9996	1539.50	29.08
1.52	9.198	0.9992	1552.69	23.35
2.08	6.054	0.9975	1523.24	22.79
3.08	5.886	0.9904	2057.27	22.3
4.08	5.64	0.9977	1712.93	20.54
5.10	5.298	0.9975	1750.85	16.97

25/2/2010				
time (h)	OUR	r2	VSS	TOC
0.00	17.658	0.9968	1680.03	35.84
0.25	16.902	0.9996	1743.52	35.88
0.53	16.302	0.9986	1702.05	31.45
1.25	13.932	0.9918	1763.69	19.33
1.77	8.856	0.9926	1772.87	18.87
2.27	6.57	0.9892	1796.52	20.51
2.77	6.672	0.9944	1800.29	24.49
3.77	6.384	0.9694	1802.17	22.37
4.77	6.318	0.9875	1872.25	21.52

Reactor 3 (8oC)

10.3.2010				
time (h)	OUR	r2	VSS	TOC
0.00	28.446	0.9994	1937.28	47.39
0.13	33.414	0.9993	2036.35	30.92
0.30	32.286	0.9997	2042.20	29.08
0.52	31.08	0.9999	1963.75	28.08
0.72	30.732	0.9998	2025.64	26.08
1.22	30.438	1	2052.35	24.64
2.33	30.204	0.9998	2066.45	23.82
3.33	25.71	0.9892	2069.07	18.57
4.33	14.52	0.9996	2088.40	7.84

11.3.2010				
time (h)	OUR	r2	VSS	TOC
0.00	23.04	0.9975	1459.13	43.66
0.17	32.376	0.9998	1533.02	42.69
0.32	31.932	0.9999	1643.33	41.91
0.52	31.308	0.9999	1631.85	39.69
1.10	28.842	0.9998	1864.72	36.96
2.20	28.134	0.9998	1603.30	18.6
2.45	26.202	0.9996	1560.50	14.79
3.52	13.512	0.9998	1724.27	5.34
4.43	13.356	0.9995	2185.82	4.27

12.3.2010				
time (h)	OUR	r2	VSS	TOC
0.00	30.486	0.9941	1511.32	56.2
0.13	32.118	0.9901	1531.97	53
0.30	30.774	0.999	1557.54	44.51
0.50	30.186	0.9911	1520.88	43.42
0.78	28.872	0.9996	1563.35	40.37
1.30	27.336	0.9999	1571.19	39.09
1.87	26.61	0.9998	1579.98	38.88
2.87	26.34	0.9978	1582.19	31.58
3.87	11.406	0.9993	1599.43	13.64

15.3.2010				
time (h)	OUR	r2	VSS	TOC
0.00	23.676	0.9994	1134.69	65.01
0.13	38.118	0.9994	1281.36	62.84
0.33	35.76	0.9996	1276.08	54.75
0.55	32.1	0.9998	1375.39	35.85
0.80	32.022	0.9997	1388.40	35.79
1.30	32.016	0.9999	1413.18	32.39
2.30	31.506	1	1400.78	25.77
3.30	17.448	0.998	1421.29	15.86
4.30	12.102	0.9983	1443.77	13.75

16.3.2010				
time (h)	OUR	r2	VSS	TOC
0.00	23.268	0.9996	1256.31	52.6
0.13	31.704	0.9998	1273.23	46.7
0.37	31.656	0.9997	1276.53	38.88
0.67	30.852	0.9999	1279.15	34.76
1.20	30.78	0.9998	1322.45	32.43
2.17	30.468	0.9993	1324.83	21.24
3.17	15.63	0.9987	1323.72	19.86
4.17	11.64	0.9962	1361.96	10.78
5.17	11.436	0.9982	1370.82	10.59

17.3.2010				
time (h)	OUR	r2	VSS	TOC
0.00	28.194	0.9994	959.73	48.7
0.22	29.004	1	1024.53	46.8
0.50	28.62	0.9997	1088.14	42.69
0.78	28.596	0.9993	1189.49	35.48
1.07	27.858	0.9993	1095.83	32.32
1.93	26.736	0.9982	1140.51	19.65
3.03	16.278	0.9798	1209.64	16.85
3.93	11.568	0.9988	1215.81	6.42
5.10	11.094	0.9985	1231.91	5.23

18.3.2010				
time (h)	OUR	r2	VSS	TOC
0.00	28.896	0.9991	1103.52	52.42
0.12	31.908	0.9999	1113.43	49.7
0.33	31.464	0.9998	1122.50	47.04
0.55	31.038	0.9998	1123.63	46.65
0.78	30.96	0.9998	1126.39	41.6
1.20	30.198	0.9998	1129.24	34.05
1.78	28.212	0.9999	1178.60	26.4
2.80	13.668	0.9977	1197.23	15.08
3.80	14.136	0.9997	1212.64	11.36

Reactor 1

date	TSS	VSS	VSS/TSS	SVI (mL/g)	mass decant (g)	mass waste (g)	total mass (g)	SRT (d)
1/27/2010	1606.9	1460.7	90.9	97.4	1.419	0.026	6.4	4.4
1/28/2010	1698.0	1412.6	83.2	82.1	1.264	0.033	5.8	4.4
1/29/2010	2007.8	1693.0	84.3	103.7	0.562	0.040	8.0	13.3
1/30/2010	2052.6	1929.2	94.0	137.8	0.561	0.038	8.2	13.7
2/1/2010	2021.2	1754.1	86.8	139.3	0.753	0.036	8.1	10.2
2/2/2010	1431.8	1165.1	81.4	109.2	0.365	0.028	4.9	12.4
2/3/2010	1412.8	1162.9	82.3	138.6	0.474	0.027	5.7	11.3
2/4/2010	1477.6	1245.3	84.3	117.0	0.117	0.028	5.9	40.6
2/5/2010	2285.0	1987.5	87.0	145.2	0.207	0.514	9.1	12.7
2/6/2010	2490.7	2076.9	83.4	146.8	0.283	0.045	10.0	30.4
2/8/2010	1858.8	1508.1	81.1	122.3	0.366	0.037	7.4	18.5
2/9/2010	1980.0	1564.9	79.0	130.3	0.383	0.037	7.9	18.9
2/10/2010	1930.9	1498.6	77.6	120.4	0.396	0.037	7.7	17.8
2/11/2010	1939.8	1402.1	72.3	104.5	0.219	0.038	7.8	30.3
2/12/2010	1658.2	1335.0	80.5	126.9	0.221	0.032	6.6	26.1
2/15/2010	1717.8	1241.0	72.2	114.7	0.555	0.032	6.9	11.7
2/16/2010	1603.5	1156.9	72.1	112.5	0.353	0.031	6.4	16.7
2/17/2010	1815.1	1346.4	74.2	118.4	0.530	0.034	7.3	12.9
2/18/2010	2057.8	1382.9	67.2	86.3	0.239	0.038	8.2	29.7
2/19/2010	1742.8	1387.9	79.6	116.0	0.165	0.033	7.0	35.3
2/22/2010	2010.0	1610.0	80.1	111.1	0.215	0.038	8.0	31.9
2/23/2010	1651.6	1328.6	80.4	127.6	0.077	0.031	6.6	61.0
2/25/2010	1868.4	1427.0	76.4	113.1	0.088	0.036	7.5	59.8
2/26/2010	2112.0	1527.4	72.3	113.6	0.233	0.582	8.4	10.4
3/1/2010	2765.8	2083.5	75.3	103.3	0.114	0.594	11.1	15.6
3/2/2010	2624.6	2046.8	78.0	111.7	0.092	0.750	10.5	12.5
3/3/2010	2513.2	1852.7	73.7	96.7	0.110	0.736	10.1	11.9
3/4/2010	2496.3	1907.5	76.4	83.8	0.155	0.708	10.0	11.6
3/5/2010	2866.4	2143.7	74.8	88.5	0.149	0.621	11.5	14.9
3/9/2010	2932.1	2123.4	72.4	83.9	0.247	0.628	11.7	13.4

	DIGESTION		
date	**TSS**	**VSS**	**VSS/TSS**
3/10/2010	2708.6	1925.5	71.1
	2702.3	1921.3	71.1
	2686.7	1878.7	69.9
3/11/2010	2591.0	1811.0	69.9
	2578.7	1813.6	70.3
3/12/2010	2620.9	1810.7	69.1
3/13/2010	2349.3	1789.1	76.2
3/15/2010	2608.9	1781.4	68.3
3/16/2010	2576.6	1762.2	68.4
3/17/2010	2578.1	1740.3	67.5
	2693.4	1737.1	64.5
3/18/2010	2493.2	1680.2	67.4
3/19/2010	2659.1	1671.5	62.9
3/22/2010	2678.2	1656.5	61.9
3/23/2010	2607.5	1647.4	63.2
3/24/2010	2507.3	1561.0	62.3
3/25/2010	1994.9	1266.9	63.5
3/26/2010	1313.1	940.6	71.6

Reactor 2:

date	TSS	VSS	VSS/TSS	SVI (mL/g)	mass decant (g)	mass waste (g)	total mass (g)	SRT (d)
1/27/2010	1128.12	875.39	77.60	94.70	0.770	0.019	1.69	2.1
1/28/2010	1017.36	846.20	83.18	84.66		0.019	1.53	
1/29/2010	1005.54	765.90	76.17	88.11	0.155	0.019	1.51	8.7
1/30/2010	1157.03	797.98	68.97	91.87	0.215	0.026	1.74	7.2
2/1/2010	1263.64	968.55	76.65	72.36	0.106	0.024	1.90	14.7
2/2/2010	1355.03	980.78	72.38	87.71	0.160	0.025	2.03	11.0
2/3/2010	1849.17	1013.43	54.80	85.79	0.111	0.036	2.77	18.9
2/4/2010	1410.53	1059.55	75.12	83.61	0.065	0.028	2.12	22.8
2/5/2010	1340.31	1028.39	76.73	161.25	0.071	0.026	2.01	20.5
2/6/2010	1388.08	1040.77	74.98	68.14	0.362	0.026	2.08	5.4
2/8/2010	1305.65	1105.08	84.64	60.13	0.221	0.025	1.96	7.9
2/9/2010	1322.22	1158.11	87.59	75.82	0.474	0.024	1.98	4.0
2/10/2010	1381.96	1187.98	85.96	73.67	0.145	0.026	2.07	12.1
2/11/2010	1324.81	1137.86	85.89	74.37	0.251	0.024	1.99	7.2
2/12/2010	1447.78	1185.43	81.88	86.11	0.206	0.028	2.17	9.3
2/15/2010	1375.00	1183.80	86.09	79.26	0.222	0.025	2.06	8.3
2/16/2010	1462.44	1184.20	80.97	94.35	0.113	0.257	2.19	5.9
2/17/2010	1504.79	1207.59	80.25	88.01	0.207	0.229	2.26	5.2
2/18/2010	1610.46	1303.81	80.96	86.08	0.086	0.211	2.42	8.1
2/19/2010	1430.31	1203.85	84.17	86.25	0.086	0.196	2.15	7.6
2/22/2010	1642.58	1328.22	80.86	67.43	0.157	0.301	2.46	5.4
2/23/2010	1607.89	1351.90	84.08	69.81	0.190	0.410	2.41	4.0
2/25/2010	1597.96	1370.97	85.79	71.44	0.065	0.467	2.40	4.5
2/26/2010	1675.31	1369.84	81.77	62.69	0.203	0.032	2.51	10.7

Reactor 3

date	TSS	VSS	VSS/TSS	SVI (mL/g)	mass decant (g)	mass waste (g)	total mass (g)	SRT (d)
3/10/2010	1340.43	959.73	71.60	67.46	0.221	0.655	4.12	4.7
3/11/2010	1566.43	1126.39	71.91	52.74	0.125	0.450	3.36	5.8
3/12/2010	1654.44	1134.69	68.58	53.05	0.216	0.512	3.28	4.5
3/15/2010	1851.31	1323.72	71.50	54.64	0.165	0.405	2.48	4.4
3/16/2010	2240.05	1459.13	65.14	60.86	0.117	0.360	2.78	5.8
3/17/2010	2188.43	1582.19	72.30	43.11	0.126	0.352	2.01	4.2
3/18/2010	2387.32	1575.79	66.01	41.46	0.134	0.336	2.35	5.0

DIGESTION			
date	TSS	VSS	VSS/TSS
3/19/2010	2139.54	1307.12	61.09
3/22/2010	1597.37	1166.69	73.04
3/23/2010	1820.49	1140.26	62.63
	1503.19	1060.17	70.53
3/25/2010	1479.18	1000.29	67.62
3/26/2010	1464.07	944.22	64.49
3/29/2010	1407.22	931.03	66.16
3/30/2010	1141.64	734.40	64.33
3/31/2010	1206.10	721.26	59.80

Hydrolysis rate (d^{-1})					
Reactor 1					
biomass	2 mars	5 mars	9 mars	**average**	Std dev
1839	1.7	1.05	1.67	**1.47**	0.367
2102	1.43	0.84	1.42	**1.23**	0.338
2388	1.22	0.67	1.23	**1.04**	0.320
2675	1.05	0.54	1.1	**0.90**	0.310
2962	0.91	0.44	1	**0.78**	0.301
Reactor 2					
biomass	22-Feb	23-Feb	25-Feb	**average**	Std dev
1235	0.35	0.15	0.28	**0.26**	0.101
1309	0.31	0.13	0.24	**0.23**	0.091
1535	0.22	0.06	0.16	**0.15**	0.081
1761	0.15	0.02	0.1	**0.09**	0.066
1986	0.1	0	0.06	**0.05**	0.050
Reactor 3					
biomass	15 mars	16 mars	18 mars	**average**	Std dev
807	2.46	2.37	2.27	**2.37**	0.095
949	2.09	1.81	1.79	**1.90**	0.168
1165	1.69	1.45	1.34	**1.49**	0.179
1381	1.43	1.22	1.07	**1.24**	0.181
1597	1.25	1.05	0.88	**1.06**	0.185

Maximum specific growth rate (d^{-1})					
Reactor 1					
biomass	2 mars	5 mars	9 mars	**average**	Std dev
1839	2.26	1.57	1.74	**1.86**	0.359
2102	1.81	1.24	1.39	**1.48**	0.295
2388	1.48	1	1.19	**1.22**	0.242
2675	1.24	0.83	0.93	**1.00**	0.214
2962	1.06	0.7	0.78	**0.85**	0.189
Reactor 2					
biomass	22-Feb	23-Feb	25-Feb	**average**	Std dev
1235	0.57	0.65	0.83	**0.68**	0.133
1309	0.51	0.59	0.75	**0.62**	0.122
1535	0.38	0.44	0.58	**0.47**	0.103
1761	0.3	0.35	0.46	**0.37**	0.082
1986	0.24	0.28	0.37	**0.30**	0.067
Reactor 3					
biomass	15 mars	16 mars	18 mars	**average**	Std dev
807	2.61	2.39	2.56	**2.52**	0.115
949	2.02	1.84	1.97	**1.94**	0.093
1165	1.49	1.36	1.44	**1.43**	0.066
1381	1.17	1.08	1.13	**1.13**	0.045
1597	0.96	0.88	0.91	**0.92**	0.040

SRT (d)	CODef	TCODef	MX_h (kgVSS)	MX_e (kgVSS)	MX_i (kgVSS)	MX_vss (kgVSS)	MX_tss (kgTSS)	V (m^3)	P_x (kgTSS/d)	MO_g (kgO/d)	MO_e (kgO/d)	MO_t (kgO/d)
1.8	114.90	133.62	6900	174	8206	15280	19100	5457	10611	3261	548.67	3809.80
2	51.82	70.54	23946	671	9118	33735	42169	12048	21085	10313	1904.22	12217.16
3	14.58	33.30	47503	1995	13677	63175	78969	22563	26323	14476	3777.43	18253.49
4	8.89	27.61	62504	3500	18237	84241	105301	30086	26325	15112	4970.32	20082.42
5	**6.59**	**25.31**	**75341**	**5274**	**22796**	**103411**	**129264**	**36932**	**25853**	**15370**	**5991.13**	**21360.74**
6	5.34	24.06	86732	7286	27355	121373	151716	43347	25286	15509	6896.95	22405.97
7	4.56	23.28	96977	9504	31914	138395	172994	49427	24713	15596	7711.63	23308.05
8	4.02	22.74	106265	11902	36473	154640	193299	55228	24162	15656	8450.17	24106.49
9	3.63	22.35	114733	14456	41032	170221	212777	60793	23642	15700	9123.54	24823.51
10	3.33	22.06	122490	17149	45592	185230	231538	66154	23154	15733	9740.40	25473.56
11	3.10	21.82	129625	19962	50151	199738	249673	71335	22698	15759	10307.78	26067.05
12	2.91	21.63	136211	22883	54710	213805	267256	76359	22271	15780	10831.52	26611.85
13	2.76	21.48	142311	25901	59269	227480	284350	81243	21873	15798	11316.53	27114.22
14	2.63	21.35	147975	29003	63828	240807	301009	86002	21501	15812	11767.01	27579.24
15	2.52	21.24	153251	32183	68387	253821	317277	90650	21152	15825	12186.54	28011.14
16	2.42	21.14	158177	35432	72946	266555	333194	95198	20825	15835	12578.22	28413.47
17	2.34	21.06	162786	38743	77506	279035	348794	99655	20517	15845	12944.75	28789.27
18	2.26	20.99	167109	42111	82065	291285	364106	104030	20228	15853	13288.49	29141.14
19	2.20	20.92	171171	45531	86624	303326	379158	108331	19956	15860	13611.51	29471.35
20	2.14	20.87	174995	48999	91183	315177	393971	112563	19699	15866	13915.63	29781.88
21	2.09	20.81	178602	52509	95742	326854	408567	116734	19456	15872	14202.47	30074.46
22	2.05	20.77	182010	56059	100301	338371	422963	120847	19226	15877	14473.45	30350.63
23	2.00	20.73	185235	59646	104861	349741	437176	124908	19008	15882	14729.87	30611.75
24	1.96	20.69	188291	63266	109420	360976	451220	128920	18801	15886	14972.87	30859.02
25	1.93	20.65	191191	66917	113979	372086	465108	132888	18604	15890	15203.47	31093.54
26	1.90	20.62	193946	70596	118538	383081	478851	136815	18417	15894	15422.61	31316.26
27	1.87	20.59	196568	74303	123097	393968	492460	140703	18239	15897	15631.11	31528.07
28	1.84	20.56	199066	78034	127656	404756	505946	144556	18069	15900	15829.74	31729.75
29	1.82	20.54	201448	81788	132215	415452	519315	148376	17907	15903	16019.18	31922.02
30	1.79	20.51	203723	85564	136775	426061	532577	152165	17753	15905	16200.05	32105.53

Q	328800.00	m3/d	TOTCOD	182.48	mgCOD/l	CODup	19.69	mgCOD/l
load	60000.00	kgCOD/d	CODb	144.07	mgCOD/l	CODus	18.72	mgCOD/l
umax	0.68	d-1	Ks	10.00	mgCOD/l	Kd	0.07	d-1

SRT (d)	CODef	TCODef	MX_h (kgVSS)	MX_e (kgVSS)	MX_i (kgVSS)	MX_vss (kgVSS)	MX_tss (kgTSS)	V (m^3)	P_x (kgTSS/d)	MO_g (kgO/d)	MO_e (kgO/d)	MO_t (kgO/d)
3	14.58	20.76	12093	508	4514	17114	21393	6112	7131	3685	961.62	4646.80
4	8.89	15.07	17873	1001	6018	24892	31114	8890	7779	4321	1421.23	5742.44
5	**6.59**	**12.76**	**22445**	**1571**	**7523**	**31538**	**39423**	**11264**	**7885**	**4579**	**1784.80**	**6363.53**
6	5.34	11.52	26386	2216	9027	37629	47036	13439	7839	4718	2098.18	6816.31
7	4.56	10.74	29880	2928	10532	43340	54175	15479	7739	4806	2376.09	7181.61
8	4.02	10.20	33023	3699	12036	48758	60948	17414	7618	4865	2626.02	7491.46
9	3.63	9.81	35875	4520	13541	53936	67420	19263	7491	4909	2852.76	7761.83
10	3.33	9.51	38478	5387	15045	58910	73638	21039	7364	4942	3059.76	8002.04
11	3.10	9.28	40867	6293	16550	63710	79637	22753	7240	4968	3249.71	8218.08
12	2.91	9.09	43067	7235	18054	68357	85446	24413	7121	4989	3424.72	8414.17
13	2.76	8.93	45103	8209	19559	72870	91088	26025	7007	5007	3586.58	8593.38
14	2.63	8.80	46991	9210	21063	77265	96581	27595	6899	5021	3736.74	8758.09
15	2.52	8.69	48748	10237	22568	81553	101942	29126	6796	5034	3876.47	8910.19
16	2.42	8.60	50388	11287	24072	85747	107184	30624	6699	5044	4006.83	9051.20
17	2.34	8.52	51921	12357	25577	89855	112319	32091	6607	5054	4128.75	9182.37
18	2.26	8.44	53358	13446	27081	93886	117357	33531	6520	5062	4243.02	9304.78
19	2.20	8.38	54708	14552	28586	97846	122307	34945	6437	5069	4350.37	9419.32
20	2.14	8.32	55978	15674	30090	101743	127178	36337	6359	5075	4451.39	9526.75
21	2.09	8.27	57176	16810	31595	105581	131976	37707	6285	5081	4546.64	9627.75
22	2.05	8.22	58307	17959	33099	109366	136707	39059	6214	5086	4636.60	9722.89
23	2.00	8.18	59378	19120	34604	113101	141377	40393	6147	5091	4721.71	9812.70
24	1.96	8.14	60392	20292	36109	116792	145990	41711	6083	5095	4802.34	9897.61
25	1.93	8.11	61354	21474	37613	120441	150551	43014	6022	5099	4878.85	9978.02
26	1.90	8.08	62268	22665	39118	124051	155064	44304	5964	5103	4951.53	10054.30
27	1.87	8.05	63137	23866	40622	127625	159532	45580	5909	5106	5020.68	10126.75
28	1.84	8.02	63966	25075	42127	131167	163958	46845	5856	5109	5086.55	10195.67
29	1.82	7.99	64755	26291	43631	134677	168347	48099	5805	5112	5149.35	10261.31
30	1.79	7.97	65509	27514	45136	138159	172699	49343	5757	5115	5209.31	10323.91

Q	328800.00	m3/d	TOTCOD	60.22	mgCOD/l	CODup	6.50	mgCOD/l
load	19800.00	kgCOD/d	CODb	47.54	mgCOD/l	CODus	6.18	mgCOD/l
umax	0.68	d-1	Ks	10.00	mgCOD/l	Kd	0.07	d-1

		Nitrate (mg/l)	Phosphate (mg/l)	Ammonia (mg/l)	Chloride (mg/l9	Sulphate (mg/l)	Sodium (mg/l)	Potassium (mg/l)	calcium (mg/l)	magnesium (mg/l)
R1	8-Feb	1.76	0.11	14.81	1513.18	219.00	889.66	44.14		
	9-Feb	3.29	0.00	17.84	1376.19	210.77	816.89	33.84		
	11-Feb	0.68	0.98		1412.76	214.30	79.28	2.62	6.59	
	12-Feb	0.74	1.25		1456.96	218.92	81.45	2.67	6.93	
	15-Feb	0.94	0.80		1505.06	223.53	82.87	2.46	6.82	
	16-Feb	3.20	0.99		1535.46	233.79	85.24	2.65	6.55	
	1-Mar	67.64	0.09	2.50	1027.22	169.41	651.67	43.54	44.16	69.49
	3-Mar	24.03		1.55	680.73	113.42	346.48	24.86	43.90	51.01
	5-Mar	25.79	0.05	1.15	645.56	112.88	394.79	24.36	36.33	44.43
	10-Mar	0.12		11.76	980.81	146.51	513.49	32.51	47.54	68.61
	17-Mar	0.49		10.86	919.13	132.52	479.92	31.07	44.89	64.10
	23-Mar	15.81		1.68	682.43	113.75	376.84	26.26	38.67	49.52
R2	5-Feb	0.12	0.02		530.55	85.62	30.97	1.47	4.19	
	8-Feb	3.45	0.00	17.80	1423.11	208.12	844.14	33.61		
	9-Feb	3.75	0.00	17.50	1407.97	220.62	850.31	34.76		
	10-Feb	0.88	0.21		1336.14	197.70	74.45	2.38	7.35	
	11-Feb	0.63	0.57		1370.67	206.22	76.26	2.48	6.04	
	15-Feb	3.07	1.12		1466.20	224.05	79.96	2.36	6.52	