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Optimization of Wastewater Treatment Plant
SAR Treatment Tananger

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Offshore Environmental Engineering

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Abstract

The focus of this thesis is optimization of the wastewater treatment plant, SART owned by SAR AS. Based on an evaluation of the present treatment condition, capacity and limitations, performance of the plant has been evaluated, with the objective of proposing optimizations in terms of increasing capacity of the plant.

The wastewater treatment plant is designed as a conventional activated sludge plant, but is currently operated as a CFSTR process. Mass balance analysis of the plant has been done accordingly.

Experimental analysis of the wastewater has shown that the received wastewater is primarily composed of readily biodegradable COD. Effluent wastewater analysis has shown that the water still contains biodegradable COD, indicating that the treatment process can be optimized further.

The performance of the plant has been determined in terms of COD removal and showed an average COD removal of 53% and an average dissolved COD removal of 83%. The low percentage of total COD removal has been found to be a result of high biomass content in the effluent.

Increasing the plant capacity in terms of flow, has been shown not to be feasible when operating the plant as a CFSTR process.

Operating the plant as an activated sludge plant by recirculating and wasting sludge has been proposed as an option to increase COD removal efficiency and to increase the plant capacity.

Keywords: Industrial wastewater treatment, Activated sludge process, Optimization, Slop water

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Abbreviations

BTEX	Benzene, Toluene, Ethylbenzene, and Xylenes
CFSTR	Continuous-Flow Stirred Tank Reactor
COD	Chemical Oxygen Demand
DAF	Dissolved Air Flotation
DO	Dissolved Oxygen
F/M ratio	Food to Microorganism ratio
LSS	Liquid phase - Static gas, Static liquid method
MEG	Monoethylene Glycol
MLSS	Mixed-Liquor Suspended Solids
MLVSS	Mixed-Liquor Volatile Suspended Solids
N	Nitrogen
OHO	Ordinary Heterotrophic Organisms
VOLR	Volumetric Organic Loading Rate
P	Phosphorous
OUR	Oxygen Uptake Rate
PFAS	Polyfluorinated Alkyl Substances
P.COD	Particulate COD
SART	SAR Treatment Tananger
SOUR	Specific Oxygen Consumption Rate
SRT	Solids Retention Time (sludge age)
TDS	Total Dissolved Solids
TEG	Triethylene Glycol
TN	Total Nitrogen

TOC	Total Organic Carbon
TSS	Total Suspended Solids
VSS	Volatile Susendend Solids

1. Introduction

Industrial wastewater may contain both biodegradable organic substances, and non-biodegradable and toxic components. One of the challenges of the wastewater treatment is a complex waste stream with large variation in composition originating from different sources. Adequate treatment of the waste water must be ensured to remove these constituents. For treatment of industrial wastewaters, the conventional technology applied is the biological activated sludge process (Orhon, Kurisu et al. 2009).

Without proper treatment discharges from the wastewater treatment plants may contain pollutants that affect the receiving waters. To minimize the effects of the pollutants in the surrounding environment, discharge regulations are established. The discharge limits should be in accordance with the type of wastewater treated and the treatment technology applied by the industry. Discharges restrictions are becoming ever more stringent and for the industry to meet the new regulations there is a continuous need to evaluate design and operation of the treatment plants.

The basic objective of a wastewater treatment plant is to ensure optimum performance, by keeping the plant in operation at lowest cost possible, while maintaining an effluent concentration below effluent discharge requirements (Orhon, Kurisu et al. 2009).

This thesis is concerned with the wastewater treatment plant SAR Treatment Tananger (SART), owned by SAR AS.

1.1 Objectives

The wastewater treatment plant experiences many operational upsets and was originally designed to handle 60,000 m^3 of wastewater per year, but today the capacity is only 40,000 m^3 per year.

SAR AS wants to ensure optimum performance of the treatment system and potentially increase the capacity of the plant based on an evaluation of the present condition, capacity and limitations. Main objective of the thesis project is to describe the current situation of treatment plant, and based on this, propose optimizations to the wastewater treatment processes.

The focus of this project is on process optimization, with emphasis on the biological treatment process.

1.2 Project Description

First step of the thesis project is to acquire a general overview of the treatment plant and operation and to identify any operational problems. This is achieved through plant visits and interview with operating personnel.

Second step of the project is to analyze the plant performance and treatment. This is achieved through review of historical operating data, and by monitoring the biological treatment process. Samples from the plant are collected for experimental assessment, to characterize the wastewater treated and for mass balance analysis of the biological treatment process.

Final step is to determine if organic removal efficiency of the plant can be optimized further as well as to identify areas for potentially increasing plant treatment capacity.

1.3 Thesis Outline

The first part of the thesis report includes a description of the background information and theory necessary for the project is given.

The second part of the report includes an introduction to the company and the treatment technology applied. Included are main findings from plant visit and interviews.

The third part of the report includes a description of the experimental assessment carried out, together with a presentation and discussion of results obtained. Finally recommended solutions, and proposed actions are presented.

2. Theoretical Background

To assess the performance of the treatment plant, literature on industrial wastewater treatment and the activated sludge process are researched.

2.1 Wastewater Characterization

Characterization of the wastewater is done physically and biologically to predict the fate of all the wastewater components in the activated sludge system. Both the organic and inorganic matter transforms physically, chemically and biologically in the bioreactor. These transformations influence both effluent quality and plant operation (Henze, Loosdrecht et al. 2011).

2.1.1 Solids Fractionation

Physical wastewater characterization in terms of solids is based on distinction between suspended (particulate/non-soluble) and soluble (dissolved) solids (Figure 1).

Suspended solids (TSS) is determined by filtration using a Whatman glass-microfiber filter with pore sizes in the range of 0.45 µm to about 2.0 µm. The fraction of solids that is retained on the filter represents TSS and solids passing through the filter is classified as dissolved solids (TDS). The suspended and dissolved solids is further subdivided into organic (volatile) and inorganic (fixed) matter by volatile suspended solids (VSS) determination by combustion. It is assumed that all organic matter will volatize by combustion at 550°C and what is left after combustion (fixed solids) represents the inorganic matter (StandardMethods 2005).

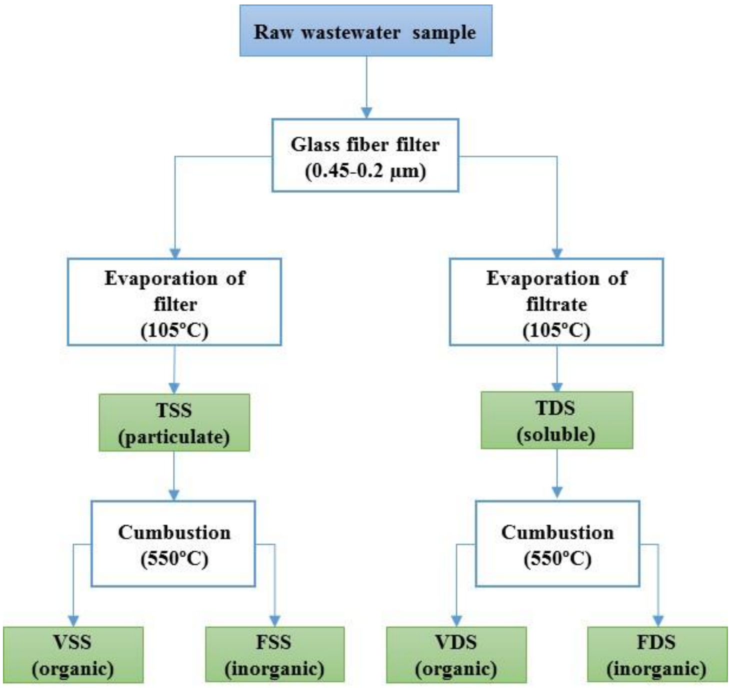

Figure 1: Wastewater solids fractionation, adapted from Tchobanoglous, Burton et al. (2014)

2.1.2 Organic Matter

Characterization of the wastewater in terms of organic carbon is an important step in the evaluation of an activated sludge system. The effluent concentration of the plant is a direct result of the conversion process happening in the biological reactor. To predict the performance of the AS system it is necessary to describe the conversion processes taking place. For organic material removal only the conversion processes apply to the biodegradable fraction of the organic matter (Henze, Loosdrecht et al. 2011, Tchobanoglous, Burton et al. 2014).

The organic matter of wastewater is considered to be made up of carbon, hydrogen, oxygen and nitrogen. The compounds are present at different oxidation states, from which some of the them can be oxidized chemically or biologically.

Measuring the organic pollution in wastewater is often performed by determination of the 5-day biochemical oxygen demand (BOD_5). BOD is a measure of the amount of dissolved oxygen consumed by microorganisms, when oxidizing the organic matter. The BOD represents only the biodegradable organic material in the water. For industrial wastewater typically a high variation in composition and organic load is observed, which demands for a quicker determination of the organic matter present and therefore total organic carbon (TOC) and chemical oxygen demand (COD) determinations are often used (Tchobanoglous, Burton et al. 2014).

The TOC analysis is a quick test, approximately 5-10 minutes and it provides an indication of the pollution of the water, but does not distinguish between biodegradable and unbiodegradable fractions of the organic matter. TOC determinations does not provide any oxidation state of the organic matter as the BOD and COD analysis (Tchobanoglous, Burton et al. 2014).

The COD analysis measures the oxygen that corresponds to organic matter in the wastewater that can be oxidized chemically using a strong oxidant, a dichromate acidic solution. The organic compounds, $C_nH_aO_bN_c$, in the wastewater is oxidized by dichromate (CrO_7^{2-}) and COD is determined as a measure of the amount of oxygen from the dichromate ion that will react with the oxidizable compounds:

$$C_nH_aO_bN_c + d\ CrO_7^{2-} + e\ H^+ \rightarrow n\ CO_2 + f\ H_2O + CNH_4^+ + 2d\ Cr^{3+}$$

Some inorganic compounds may also be oxidized by dichromate, which may increase the COD result. The analysis can be carried out in approximately 2.5 hours (Tchobanoglous, Burton et al. 2014).

COD represents both the biodegradable and the unbiodegradable organic carbon fractions in wastewater, and the COD is further divided into fractions of biodegradable and unbiodegradable COD, Figure 2 (index i indicates influent, and e indicates effluent).

All biodegradables (S_{bi}) will transform into ordinary heterotrophic organisms (OHO's), which then becomes part of the organic suspended solids (the VSS) in the bioreactor. The biodegradable COD (S_b) is further subdivided into readily biodegradable and slowly biodegradable. The readily biodegradable COD (S_{bs}) is considered soluble and the slowly biodegradable matter, (Sbp), is considered particulate.

The unbiodegradable COD (X_I) is considered to be inert and passes through the system unchanged and is further subdivided into particulate COD and soluble COD. The unbiodegradable soluble COD (S_{us}) leaves the system with the effluent. The unbiodegradable particulate COD (S_{up}) becomes enmeshed with the sludge (the VSS) and is removed through sludge wasting (StandardMethods 2005, Henze, Loosdrecht et al. 2011).

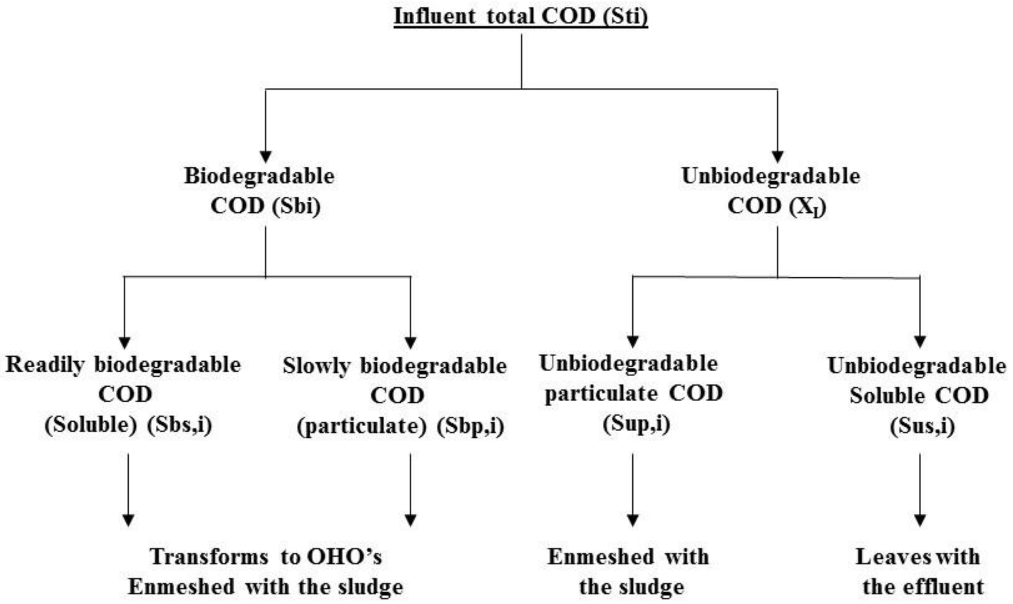

Figure 2: COD fractionation adapted from(Henze, Loosdrecht et al. 2011), Tchobanoglous, Burton et al. (2014)

Typical COD concentration for untreated raw municipal wastewater is 750 mg COD/L. The fractions of $S_{up,i}$ is 0.15 and $S_{us,i}$ is 0.07 of the total influent COD (Henze, Loosdrecht et al. 2011).

2.1.2.1 Relationship between COD and TOC

For industrial wastewater a stoichiometric COD/TOC ratio ranging from 0 (for non-oxidizable organics) and up to 5.33 (for methane) can be expected. For a highly variable wastewater a greater change in the ratio will be observed (Agency 1973).

A pre-feasibility study has been done for a wastewater treatment plant located in Mongstad and owned by SAR AS (COWI 2015). The study was on wastewater with different compositions to be treated at the plant. Findings showed that wastewater received from offshore contained significant amounts of dissolved methanol, monoethylene glycol (MEG) and triethylene glycol (TEG), production chemicals used offshore. For these wastewaters a

COD/TOC ratio of 3.3 and 4.2 were assumed. It is not unlikely that the wastewaters received at the treatment plant in Tananger has similar composition. Furthermore, the influent wastewater at SART may contain phenol and aromatic hydrocarbons, such as BTEX (Alsvik 2015).

The theoretical COD can be calculated for a substrate using a general equation, where organic matter is the electron donor and oxygen is the electron acceptor

$$Organic\ matter + xO_2 \rightarrow xCO_2 + xNH_3 + xH_2O$$

The equation is balanced according to the substrate with the stoichiometric coefficient, x, and 1 g O_2 equals -1 g COD (Tchobanoglous, Burton et al. 2014).

From this a theoretical COD/TOC ratio can be estimated, using methanol (CH_4O) as example

$$CH_4O + 1.5O_2 \rightarrow CO_2 + 2H_2O$$

Molecular weight of CH_4O = 32 g/mol and for $1.5O_2$ = 48g/mol

$$COD(CH_4O) = \frac{48\ g\ O_2/mol}{32\ g\ CH_4O/mol} = 1.5gO_2/gCH_4O$$

$$TOC(CH_4O) = \frac{1 \cdot 12\ g\ TOC/mol}{32\ g\ CH_4O/mol} = 0.375g\ TOC/gCH_4O$$

$$COD/TOC\ \ ratio\ (CH_4O) = \frac{1.5gO_2/gCH_4O}{0.375g\ TOC/gCH_4O} = 4$$

Table 1 shows calculated theoretical COD/TOC ratios of various compounds that may appear in the wastewater treated at SART Tananger; the ratios are all above three.

Table 1: Calculated theoretical COD/TOC ratio of various compounds

Substance	*COD/TOC ratio (calculated)*
Methanol	4.00
Phenol	3.11
MEG	3.33
TEG	3.33
Methane	4.00
Benzene	3.33
Toluene	3.43
Ethylbenzene	3.50
Xylene	3.50

For organic material removal it is adequate only to characterize the water in terms of total COD, biodegradable and non-biodegradable (inert) soluble and particulate COD (Wentzel, Mbewe et al. 1999).

2.1.3 Effluent Quality

For an activated sludge plant operating under optimal conditions it can be assumed that all soluble biodegradable organic matter is degraded within the solids retention time, and what should be left in the effluent is the unbiodegradable soluble COD. Particulate biodegradable and unbiodegradable organic matter will be enmeshed in the sludge and is settled in the settling tanks (Henze, Loosdrecht et al. 2011).

To characterize the COD in the effluent and to determine if any biodegradables are left in the effluent, a batch reactor test can be run with a sample of the effluent collected from the plant. Filtered COD (COD_S) is determined using a standard glass-microfiber filter with pore sizes in the range of 0.45 µm to about 2.0 µm. Experimental period should be 10-14 days, or until the concentration of COD_S remains constant (Kommedal 2016). If biodegradables are present in the effluent, the initial concentration of COD_S makes up the soluble biodegradable and unbiodegradable COD_S ($S_{bs,e} + S_{us,e}$). And the final constant COD_S concentration represents the fraction of unbiodegradable soluble COD ($S_{us,e}$). The fraction of $S_{bs,e}$ is then found by difference.

Particulate COD can be measured by difference in total and soluble COD determinations. Final particulate COD represents the particulate unbiodegradable COD ($S_{up,e}$) plus the new biomass formed. For municipal wastewater $S_{up,e}$ equals approximately 10% of the total COD. For industrial wastewater the fraction of unbiodegradable are typically higher in the influent than municipal wastewater (Ystedbø 2016).

Additionally, the amount of biodegradable organic matter left in the effluent can be determined by BOD analysis for comparison, both for total and dissolved BOD.

2.2 Pretreatment

The biological treatment process operates most effectively at constant conditions. For industrial wastewater, typically variations in organic load, salt concentrations and toxicity are observed. These variations are not always compatible with the biological treatment and equalization should be provided to buffer the production against these variations. Equalization tanks should be completely mixed and can be operated with constant or variable flow (Eckenfelder and Musterman 1995, Orhon, Kurisu et al. 2009).

Pretreatment of the wastewater is done to remove pollutants, which are not compatible with the optimal performance of the activated sludge process and to enhance biodegradability (Eckenfelder and Musterman 1995).

Pretreatment by dissolved air flotation is used to separate solid or liquid particles from a liquid phase. Flotation is applied instead of sedimentation to remove oil and grease and to enhance the separation of small and light particles that settle slowly, and also for limited plant space. DAF can be enhanced by chemical addition (Tchobanoglous, Burton et al. 2014).

The purpose of the chemical treatment is to form particulates that can be separated in the flotation process. Addition of chemicals will facilitate chemical precipitation by altering the physical state of the dissolved and suspended solids present in the wastewater. It is possible to remove 80 to 90% of the total suspended solids including some colloidal particles and 50 to 80% of the BOD by chemical precipitation. Also removal of heavy metals and dissolved inorganic substances is achieved. Furthermore, using polymer as flotation aid can increase the solids recovery from 85 to 98 or 99% (Tchobanoglous, Burton et al. 2014).

For the flotation process, air is dissolved into the liquid phase under pressure. When releasing the air saturated wastewater into the flotation tank, the pressure drops to atmospheric pressure and microbubbles will form. Particles will adhere to the air bubbles, increasing their buoyancy and making them rise to the surface. A floating layer of sludge is formed, which can be skimmed off for further processing (Tchobanoglous, Burton et al. 2014).

Factors influencing performance of the chemical precipitation are pH, mixing efficiency, temperature or residence time. Optimal conditions should be determined by a study and to optimize the chemical use, analysis could be done to identify potentially better chemicals (Ystedbø 2016). An evaluation to assess alternative chemicals in the process could be performed, including:

- Test of different chemicals, flocculants and coagulants.
- Chemical dosage (tested in lab by jar test and titrations).
- Mixing conditions, including pH, temperature and alkalinity.

This analysis would require a separate project in itself.

2.3 Biological Treatment – Activated Sludge Process

In biological wastewater treatment microorganisms are used to oxidize the dissolved and particulate organic matter present in the water.

A complete-mix activated sludge process is applied (Figure 3). The activated sludge process consists of three parts: (i) an aerobic biological reactor, where microorganisms are kept in suspension with vigorous mixing and aeration; (ii) settling tank, where liquid and solid separation takes place; and (iii) a recycle system for returning activated sludge settled in the settling tank back to the bioreactor.

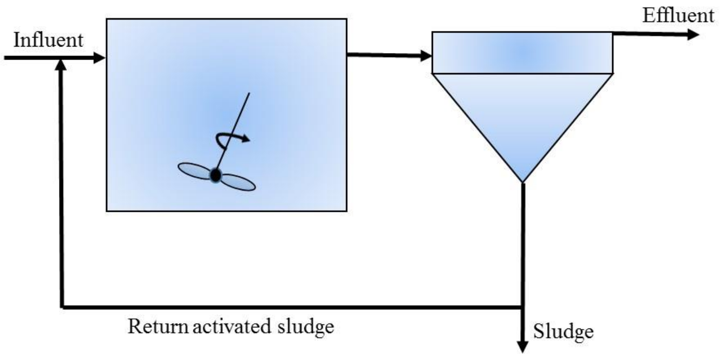

Figure 3: Complete mix activated sludge process

The aim of the activated sludge process is to remove the organic matter in the wastewater by converting it into a flocculent suspension that will settle easily by gravitation in the settling tank.

In the bioreactor mechanical equipment is used to mix and aerate the feed wastewater with the suspended microorganisms, making up the mixed-liquor suspended solids (MLSS). The bioreactor is completely mixed ensuring uniform distribution of the organic load, MLSS concentration and oxygen demand; also making it more resistant to shock loads due to dilution. Microorganisms convert the organic matter in the wastewater into simpler products, such as new biomass, carbon dioxide and water. The mixed-liquor is pumped to the settling tank, where the sludge (with high fraction of active biomass) settles by gravity settling. Part of the settled sludge is returned to the biological reactor as return activated sludge (Tchobanoglous, Burton et al. 2014).

The cleared effluent is removed from the top of the settler and is discharged to the receiving waters. To maintain a set solids retention time (SRT) and avoid accumulation of solids (excess biomass production + unbiodegradable solids) in the bioreactor part of the sludge is wasted daily. If accumulated solids are not removed, this may result in the solids eventually flowing to the effluent. Sludge wasting can be from the settler tank underflow recycle line or alternatively from biological reactor (Henze, Loosdrecht et al. 2011).

2.3.1 Microbiology in the activated sludge system

In order for the microorganisms to grow they need to synthesize new cell material, which requires energy, carbon and other nutrients.

The microorganisms are made up of 75-80% water and 20-25% dry matter. The dry matter of the microorganisms is both organic and inorganic, and about 50% of the dry matter is made up of carbon. All cells require sources of carbon, heterotrophic microorganisms obtain their carbon from organic compounds and autotrophic microorganisms from carbon dioxide. Besides carbon the essential components needed for a cell are oxygen, nitrogen and hydrogen, phosphorous, plus more (Henze, Loosdrecht et al. 2011).

Industrial wastewater with high organic loading, may be limited in nitrogen and phosphorous, which will affect biomass growth, and nutrients need to be supplied (Tchobanoglous, Burton et al. 2014).

The carbon and energy source is described as organic matter or substrate in the following.

The energy required for growth is generated by biochemical reactions, microbial metabolism is the sum of all these reactions taking place in the living cells. The energy is produced through chemical oxidation reactions requiring an electron donor and acceptor. For organic matter removal only using the aerobic activated sludge system, the electron donor is the organic matter (or ammonium) and the electron acceptor is oxygen (or oxidized nitrogen, nitrate or nitrite).

Aerobic biological oxidation of organic matter

$$v_1(organic\ matter) + v_2O_2 + v_3NH_3 + v_4PO_4^{3-} \xrightarrow{microorganisms} v_5(new\ cells) + v_6CO_2 + v_7H_2O$$

v_i is the stoichiometric coefficient (Tchobanoglous, Burton et al. 2014).

2.3.2 Nutrient requirements

The required amount of nitrogen (N) and phosphorous (P) per grams of biomass (BM) formed can be calculated theoretically. The empirical formula for biomass is $C_{60}H_{87}O_{23}N_{12}P$ (Tchobanoglous, Burton et al. 2014).

From this it is seen that 12 mol N and 1 mol of P is required per mol of biomass. Molecular weight of N is 14 g/mol and of P is 31 g/mol. Molecular weight of BM is 1374 g VSS/mol BM.

N requirement per grams of biomass:

$$\frac{12\ mol\ N/mol\ BM \cdot 14g\ N/mol\ N}{1374\ gVSS/mol\ BM} = 0.122\ g\ N/g\ VSS$$

The COD/VSS ratio of the sludge (f_{cv}) is 1.48 g COD/g VSS.

N requirement per grams of COD:

$$\frac{0.122\ g\ N/g\ VSS}{1.48\ g\ COD/g\ VSS} = 0.0826\ g\ N/g\ COD$$

P requirement per grams of biomass:

$$\frac{1\ mol\ P/mol\ BM \cdot 31g\ P/mol\ N}{1374\ gVSS/mol\ BM} = 0.0225\ g\ P/g\ VSS$$

P requirement per grams of COD:

$$\frac{0.0255\ g\ P/g\ VSS}{1.48\ g\ COD/g\ VSS} = 0.015\ g\ N/g\ COD$$

Table 2: N/COD and P/COD ratios

N/COD (g N/g COD)	0.0826
P/COD (g P/g COD)	0.0225

From the N and P ratios, the amount of N and P required for a wastewater can be determined from the yield coefficient and the biodegradable COD concentration of a specific wastewater. The amount of nutrients removed for biomass growth, can be evaluated as a function of the ratios, COD/N and COD/P of the influent wastewater (Orhon, Kurisu et al. 2009).

The amount of nitrogen required for a specific wastewater is calculated by

$$N\ required = \frac{1}{f_s \cdot 0.0826 \cdot Y_H}$$

Where f_s is fraction of total influent biodegradable COD to the total influent COD (S_{bi}/S_{ti}) and Y_H is the heterotrophic yield coefficient. The COD/N fraction of a wastewater should be equal to or less than the required nitrogen.

The same can be calculated for phosphorous

$$P\ required = \frac{1}{f_s \cdot 0.0225 \cdot Y_H}$$

The COD/P fraction of a wastewater should be equal to or less than the required phosphorous.

The heterotrophic yield coefficient for the wastewater treated at SART has previously been estimated to an average of 0.22 mg VSS/mg COD corresponding to 0.33 mg COD/mg COD (Aulie 2006).

2.3.3 Microbial Growth

For a batch mode, biomass growth can be described by the four phases shown in Figure 4: (1) The lag phase, the phase where the microorganism adapts to the new environment before actual biomass growth occurs, and almost no substrate is consumed. (2) The exponential growth phase is where regular constant cell division occurs. Consuming most of the substrate which is readily available, the growth rate of the biomass is at maximum. (3) The stationary phase, where there is no net increase or decrease in cell number due to limiting substrate concentration or accumulation of toxic metabolites. (4) The final phase is the decay phase, where substrate has been depleted and the biomass decline (Madigan, Martinko et al. 2015).

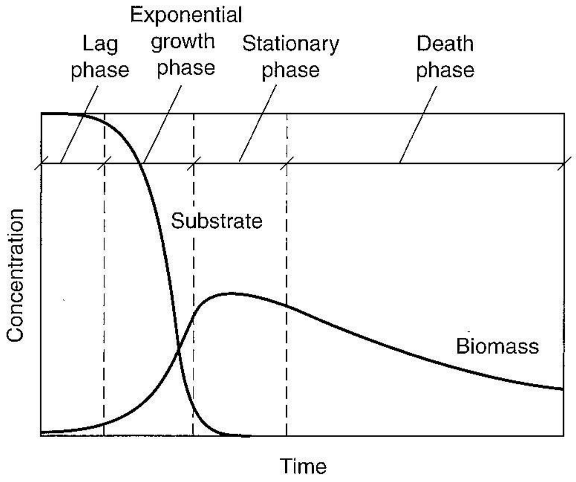

Figure 4: Growth phases and concentration of substrate and biomass over time in a batch process (Tchobanoglous, Burton et al. 2014)

The growth of biomass in the biological reactor can be estimated by measuring particulate organic matter. This is done either by volatile suspended solids determination of the mixed-liquor (MLVSS) or by measuring particulate COD (Tchobanoglous, Burton et al. 2014).

2.3.4 Factors affecting Performance of Biological Treatment

Other factors that can affect the growth of microorganisms are mixing regime in the bioreactor, dissolved oxygen concentration, temperature, pH, salinity, and toxicity (Henze, Loosdrecht et al. 2011, Tchobanoglous, Burton et al. 2014).

- Adequate mixing in the biological reactor is important to ensure uniform distribution of the organic load, oxygen and nutrients. Sufficient mixing would result in an effluent flow from the reactor having the same composition as in the biological reactor.
- Temperature has a great influence on growth of microorganism. Optimum temperature is dependent on the group of microorganisms present in the bioreactor and a temperature to high will result in the denature of the microorganisms. Mesophile microorganisms are in the temperature range from 15-40°C, with a maximum growth rate at approximately 40°C.
- Sufficient oxygen for the biological conversion process needs to be supplied. Common DO concentration in the bioreactor is 2.0 mg/L.
- pH in the bioreactor should be in the range of 6.0 to 9.0, with optimal growth conditions for most microorganisms in a pH range between 6.5 and 7.5.
- Salinity may normally affect the growth of microorganisms, but the microorganisms used at SART has been adapted to the high salinity conditions found in the treated wastewater. Salinity approaching that of seawater (35 ppt) will not affect the microorganisms, but concentrations higher than that should be avoided (SART).

- Toxic compounds present in the wastewater, in the form of biocides, have been observed in the water treated at SART. The biocides are normally not removed in pretreatment and are not compatible with the microorganism and may therefor inhibit the process or potentially result in cell lysis (SART).

2.3.5 Control and Analysis of the Activated Sludge Process

The activated sludge process is made up of a large number of variables and to ensure a high level of treatment performance process control is essential.

2.3.5.1 Solids Retention Time

Controlling the sludge age is an essential part of the process control. The sludge age or solids retention time is the average time the solids are kept in the system. The SRT is controlled by the amount of sludge wasted daily (Tchobanoglous, Burton et al. 2014).

The SRT for the activated sludge process is defined by

$$SRT = \frac{X_t \cdot V}{Q_e \cdot X_{t,e} + Q_w \cdot X_{t,r}}$$

Where, $X_{t,e}$ is the solids leaving with the effluent, and $X_{t,r}$ is the solids leaving with the waste. Q_e is the effluent flow and Q_w is the waste flow rate.

Typical SRT for the complete mix activated sludge process is 3-15 days.

2.3.5.2 Sludge Wasting

Wasting of sludge can be done directly from the bioreactor or from the sedimentation tank return sludge line (Tchobanoglous, Burton et al. 2014). At SART wasting is designed to be from the return sludge line.

Then the SRT definition can be used to determine the amount of sludge to be wasted. Assuming that all solids have settled in the sedimentation tank, and the solids concentration in the effluent is negligible, $X_{t,e} = 0$, the expression for SRT becomes

$$SRT = \frac{X_t \cdot V}{Q_w \cdot X_{t,r}}$$

Rearranging the equation solving for Q_w

$$Q_w = \frac{X_t \cdot V}{X_{t,r} \cdot SRT}$$

This way the sludge wasting flow rate can be determined by measuring concentration of solids in the bioreactor and in the recirculated sludge.

2.3.5.3 Dissolved Oxygen

Other typical control parameters include maintaining an adequate dissolved oxygen concentration in the bioreactor, approximately 1.5 to 2 mg/L. The required oxygen is theoretically the amount of oxygen needed for the microorganisms to degrade the organic matter present. At limiting oxygen concentration, filamentous microorganism may become dominating, resulting in poor settling characteristics of the sludge (Tchobanoglous, Burton et al. 2014).

2.3.5.4 Sludge Recycle Rate

To maintain and adequate concentration of MLSS (active biomass) in the bioreactor, the amount of return activated sludge can be controlled (Orhon, Kurisu et al. 2009, Tchobanoglous, Burton et al. 2014). For the activated sludge process, the recycle ratio, R, of the activated sludge is defined by

$$R = \frac{Q_r}{Q}$$

Where Q is the influent flowrate to the bioreactor and Q_r is the sludge recycle flowrate. This is a parameter that can be determined from the sludge (MLSS) sedimentation properties. The sludge recycle rate can be found by mass balance around the sedimentation tank, Figure 5.

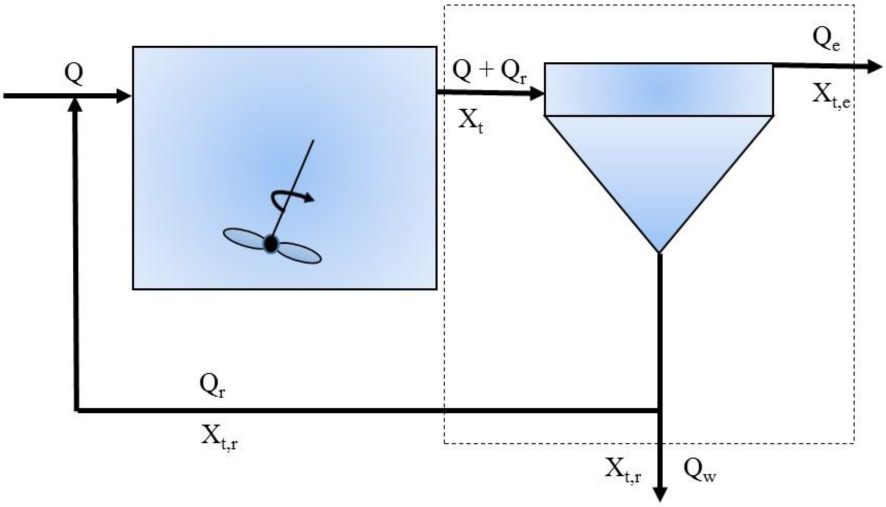

Figure 5: Mass balance around the bioreactor for sludge recycle determination

Accumulation = inflow - outflow

$$0 = X_t(Q + Q_r) - Q_r \cdot X_{t,r} - Q_w \cdot X_{t,r} - Q_e \cdot X_e$$

Assuming that all solids have settled in the sedimentation tank, $X_{t,e}$ is negligible, and that $Q_w X_{t,r}$ can be related to the defined SRT, the mass balance equation can be solved for Q_r

$$Q_r = \frac{X_t \cdot Q - (X_t \cdot V/SRT)}{X_{t,r} - X_t}$$

Inserting the expression of the recycle ratio the equation can be rearranged

$$Q_r = \frac{1 - \frac{HRT}{SRT}}{\frac{X_{t,r}}{X_t} - 1} \cdot Q$$

For high SRT values the recycle ratio equation can be simplified

$$R = \frac{X_t}{X_{t,r} - X_t}$$

$X_{t,r}$ can be estimated from the sludge settling properties, measured by the sludge volume index, SVI (mL/g), defined by

$$SVI = \frac{V_S}{X_t} = \frac{(Volume\ of\ settled\ sludge, mL/L) \cdot (10^3 mg/g)}{(suspended\ solids, mg/L)}$$

SVI is determined experimentally by settleability analysis, letting the sludge settle for 30 minutes. $X_{t,r}$ can be estimated from correlation with the SVI, assuming that the SVI approximates the biomass settling

$$X_{t,r} \approx \frac{10^6}{SVI}$$

From an estimate of $X_{t,r}$ it will be possible to estimate the recycle ratio, and hence the sludge recycle flowrate.

A sludge with a SVI value of 100 mL/g is considered a good settling sludge and SVI values below 100 are desired. Sludge with values higher than 120 mL/g is considered as bulking sludge. For bulking sludge, the MLSS settles poorly and will be carried to the sedimentation tank effluent.

Bulking sludge can be caused by growth of filamentous organisms. Or it can be caused by viscous bulking, due to excessive concentration of extracellular biopolymer. Viscous bulking is often observed for nutrient-limited systems or for wastewaters with high amount of readily biodegradable COD. The MLSS can be investigated by microscope to determine the microbial growth and if filamentous organisms are present.

Typical return activated sludge range for a complete-mix activated sludge process is 25 - 100% of the influent flow, with a typical concentration range of 4000 to 12,000 mg/L. The recommended MLSS concentration in the bioreactor is 3000 to 4000 mg/L. Values above 5000 mg/L may lead to overloading of the sedimentation tank

2.3.5.5 Food to Microorganism Ratio and Volumetric Organic Loading Rate

Evaluating the operating conditions of the activated sludge process may be done by analyzing the food to microorganism ratio (F/M ratio) and the volumetric organic loading rate (VOLR) and comparing these with typical expected values (Tchobanoglous, Burton et al. 2014).

The F/M ratio is the amount of substrate available to the amount of microorganisms present in the bioreactor. Typical F/M ratio for the complete mix activated sludge process is 0.2 - 0.6 kg BOD/kg MLVSS·day.

The VOLR is the amount of BOD or COD applied to the bioreactor volume per day. Values range from 0.3 to more than 3.0 and the typical OLR for the complete mix activated sludge process is 0.3 – 1.6 kg BOD/m^3·d. A high loading rate will generally lead to higher DO requirements in the bioreactor.

2.4 Mass Balance Analysis

According to Orhon, Kurisu et al. (2009) assessment of the activated sludge process performance requires analysis of some fundamental system functions, such as:

- Amount of biomass in the reactor
- Excess biomass generated
- Effluent quality
- Amount of oxygen utilized
- Recycle ratio
- Nutritional requirements.

A mass balance analysis will provide information about what takes place in the defined system of interest (a bioreactor) as a function of time. The analysis will describe reaction kinetics and reactor hydraulics for each component in the system and can be used to evaluate the system functions.

2.4.1 Conversion Model

The mass balances require a conversion model describing reaction rate terms for the depletion or production of the components. For this purpose, the traditional modelling approach can be used (Spanjers 1998). The model includes two conversion processes, aerobic growth and decay of heterotrophic biomass, and both processes are considered to consume oxygen (Figure 6). Growth of the biomass, X_H, is considered to be a result of utilization of the readily biodegradable substrate (S_{bs}). The slowly biodegradable substrate (S_{bp}) is considered to become entrapped into the biomass flocs and here it is converted to readily biodegradable substrate through hydrolysis.

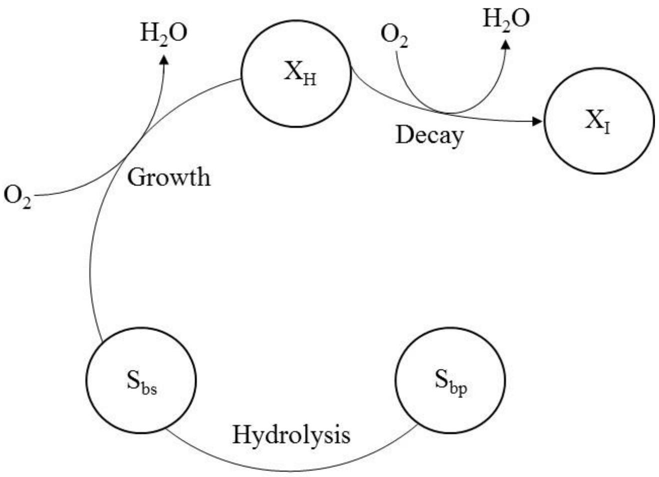

Figure 6: Main processes for heterotrophic growth and biodegradation using the traditional modelling approach, adapted from Spanjers (1998)

The yield of biomass, Y_H, in the growth process is defined as the ratio of the amount of biomass produced in the activated sludge system to the amount of substrate consumed

$$Y_H = \frac{g\ biomass\ produced}{g\ substrate\ utilized} = \left[\frac{g\ VSS}{g\ COD}\right]$$

The growth rate of biomass, r_g, is described by

$$r_g = \mu \cdot X_H$$

Where μ is the specific biomass growth rate. The specific growth rate is substrate limited and assumed to follow Monod kinetics

$$\mu = \mu_{max} \frac{S}{K_S + S}$$

Where μ_{max} is the maximum growth rate and K_S (g COD/ m^3) is the half saturation coefficient.

It is assumed that when the readily and slowly biodegradable substrate has been depleted (or in the absence of biodegradable substrate), the observed oxygen consumption will be a result of biomass decay only. The respiration rate (endogenous respiration) will decrease gradually until all biomass has decayed. The decaying biomass is oxidized contributing to the inert matter, X_I (Figure 6). The fraction of inert organics formed by decay of biomass, f_I is determined by

$$f_I = \frac{COD(X_I)}{COD(X_H)}$$

Matrix presentation of the model with process rate equations is shown in Table 3, autotrophic microorganism is assumed not to be present. The two conversion processes defined in the model are listed in the left column and the process rate for each of them are listed in the right column. The kinetic parameters for the process rates are defined in the bottom of the table to the right. The stoichiometric coefficients of the model are listed in the body of the table and the definition of these in the bottom of the table to the left. Negative sign is for consumption and positive for production. Components are presented as COD equivalents.

Table 3: Matrix representation of the activated sludge model with process rate equations (Çokgör, Sözen et al. 1998, Kommedal 2015)

Component → *i* *j* Process ↓	1 X_H	2 X_I	2 S	3 O_2	Process Rate, ρ_j (COD/m^3·d)
1 Growth (r_g)	1		$-\frac{1}{Y_H}$	$-\frac{1-Y_H}{Y_H}$	$\mu \cdot X_H$
2 Decay (r_d)	-1	f_I		1- f_I	$b_H \cdot X_H$
Observed conversion rate, r_i	$r_i = \sum_j \nu_{ij}\rho_j$				Defined kinetic Parameters: μ_{max} = Maximum specific growth rate K_S = Half-saturation constant b_H = Decay coefficient
Stoichiometric Parameters: Y_H = Heterotrophic yield coefficient f_I = Fraction of inorganics	Biomass (COD/m^3)	Inert organics (COD/m^3)	Organic substrate (COD/m^3)	Dissolved oxygen (- COD/m^3)	

Example using the matrix to describe the rate of oxygen consumed for decay

$$r_i = \sum_j \nu_{ij}\rho_j = r_{O_2} = (1 - f_I) \cdot b_H \cdot X_H$$

The stoichiometric and kinetic coefficients, i.e. the yield coefficient, Y_H, the fraction of inorganics, f_I, the maximum specific growth rate, μ_{max}, and the decay coefficient, b_H, may be determined experimentally for a specific wastewater (Ekama, Dold et al. 1986).

The decay coefficient for the wastewater treated at SART is unknown and will not be estimated in this thesis. The decay coefficient has been estimated for municipal wastewater and this can be used instead (Henze, Loosdrecht et al. 2011). The standard value of the decay coefficient at 20°C is 0.24 (1/d). The coefficient is temperature dependent and can be estimated for a specific temperature, T, using Arrhenius equation

$$b_{H,T} = b_{H,20} \cdot \theta^{(T-20)}$$

Where $\theta = 1.029$.

2.4.2 System Boundary

Next step of the mass balance analysis is then to define a system boundary to describe the flows into and out of the system. Currently the wastewater treatment plant is not operated as a conventional activated sludge process, since no sludge is recirculated or wasted (this is discussed in chapter 3). The biological treatment can then be considered as a continuous-flow stirred tank reactor (CFSTR) and the mass balance analysis is done accordingly (Kommedal 2015). System boundary for the mass balance analysis will then only include the bioreactor, with only one input and one output stream, Figure 7.

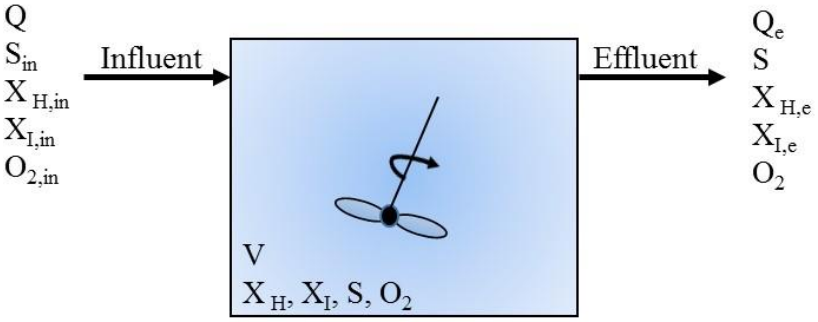

Figure 7: Bioreactor with influent and effluent components used for the mass balance analysis (Kommedal 2015)

The reactor with volume, V (m^3) is assumed to be an ideal CFSTR with a feed flow rate, Q (m^3/h). The influent is made up of feed substrate, S_{in} (g COD/ m^3), active heterotrophic biomass, X_H (g COD/ m^3), inert organics, X_I (g COD/ m^3), and with a dissolved oxygen concentration, $O_{2,in}$ (g COD/ m^3). Assumptions for the analysis are complete mixing in the reactor, constant inlet conditions $\frac{d}{dt}(C_i, in) = 0$, and two conversion processes takes place, biomass growth and decay.

The MLSS concentration (X_t) in the bioreactor is a function of the organic (X_{VSS}) and inorganic (X_{IO}) particulates

$$X_t = X_{VSS} + X_{IO}$$

The fraction of inorganic particulates, in the system are considered negligible, since it is assumed that these are removed by pretreatment, and the MLSS concentration then comprises the organic particulates.

2.4.3 Mass Balance Equations

A general mass balance for the components in the system is described as:

$$\begin{bmatrix} Mass \\ accumulation \\ in\ the\ system \end{bmatrix} = \begin{bmatrix} Mass\ flow \\ into\ the\ system \end{bmatrix} - \begin{bmatrix} Mass\ flow \\ out \\ of\ the\ system \end{bmatrix} + \begin{bmatrix} Conversion \\ of\ mass \\ in\ the\ system \end{bmatrix}$$

Presented mathematically

$$\frac{dC}{dt}V = Q(C_{in} - C_{out}) + r_c \cdot V$$

Where C represents the component of interest and r_c, is the conversion rate for this component, defined in the conversion model, Table 3. A mass balance for each component in the system can be defined with conversion rate expressions inserted. To simplify the solutions of the equations, steady state is assumed and the rate of accumulation then becomes zero $\left(\frac{dC}{dt}V \cong 0\right)$.

$$V\frac{dS}{dt} = Q(S_{in} - S) + r_s \cdot V = Q(S_{in} - S) - \frac{\mu \cdot X_H}{Y_H} \cdot V \cong 0$$

$$V\frac{dX_H}{dt} = Q\left(X_{H_{in}} - X_H\right) + (r_g + r_d) \cdot V = Q\left(X_{H_{in}} - X_H\right) + X_H(\mu - b_H) \cdot V \cong 0$$

$$V\frac{dX_I}{dt} = Q\left(X_{I_{in}} - X_I\right) + r_d \cdot V = Q\left(X_{I_{in}} - X_I\right) + f_I \cdot b_H \cdot X_H \cdot V \cong 0$$

$$V\frac{dO_2}{dt} = Q\left(O_{2_{in}} - O_2\right) + (r_g + r_d) \cdot V = Q\left(O_{2_{in}} - O_2\right) - \left(\frac{1 - Y_H}{Y_H} \cdot \mu + (1 - f_I)b_H\right) \cdot X_H \cdot V \cong 0$$

The mass balances can be solved to for each component to find the steady state solutions.

2.4.4 Effluent Substrate Concentration

The concentration of substrate in the effluent is first found. Assuming that the inlet biomass is negligible, $X_{H,in}$ =0, which is higly likely for industrial wastewater , the biomass steady state mass balance is simplified

$$Q(-X_H) + X_H(\mu - b_H) \cdot V \cong 0 \Leftrightarrow$$

$$Q \cdot X_H = X_H(\mu - b_H) \cdot V \Leftrightarrow Q/V = (\mu - b_H)$$

A system dilution rate, D, is defined as the rate at which the biomass is diluted

$$D = \frac{Q}{V}$$

For a constant reactor volume and no biomass entering the system, an increasing inlet flow will dilute the concentration of biomass until it becomes zero at D_{max}, Figure 8.

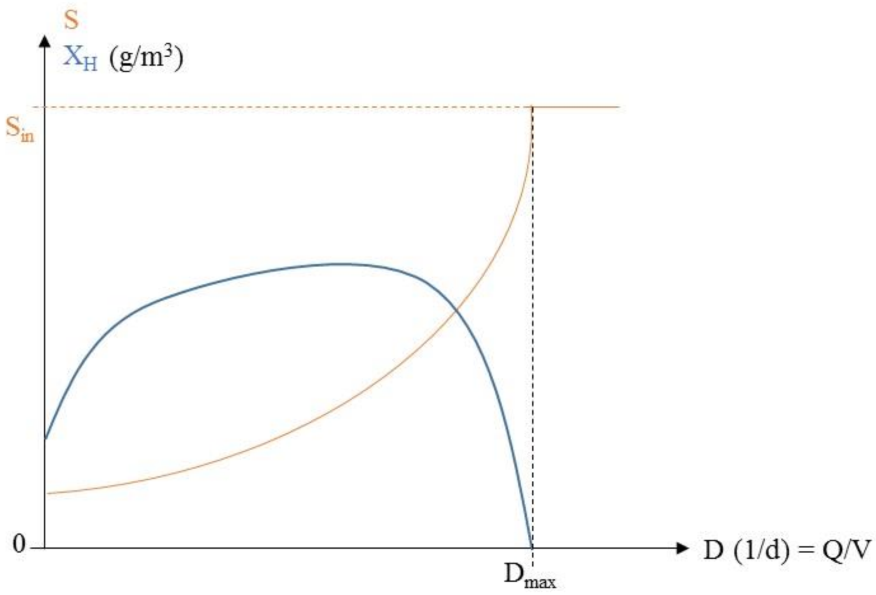

Figure 8: Substrate and biomass concentrations as a function of system dilution rate (Kommedal 2015)

This further simplifies the biomass mass balance equation

$$D = \mu - b_H$$

The expression for specific growth rate, μ, is inserted and the equation rearranged and solved to find the effluent substrate concentration

$$D = \mu_{max} \frac{S}{K_S + S} - b_H \Leftrightarrow (D + b_H)(K_S + S) = \mu_{max} \cdot S \Leftrightarrow$$

$$K_S(D + b_H) + S(D + b_H) = \mu_{max} \cdot S \Leftrightarrow K_S(D + b_H) = \mu_{max} \cdot S - S(D + b_H) \ \Leftrightarrow$$

$$K_S(D + b_H) = S \cdot (\mu_{max} - (D + b_H)) \Leftrightarrow$$

$$S = \frac{K_S(D + b_H)}{\mu_{max} - (D + b_H)}$$

The effluent substrate concentration is thus not dependent on the inlet substrate concentration, but only dependent on the dilution rate of the system.

2.4.5 Active Heterotrophic Biomass

To find the effluent biomass concentration, the substrate steady state mass balance is solved. Using the defined dilution rate, the mass balance is simplified

$$Q(S_{in} - S) = \frac{\mu \cdot X_H}{Y_H} \cdot V \Leftrightarrow D(S_{in} - S) = \frac{\mu \cdot X_H}{Y_H}$$

Knowing that $\mu = D + b_H$ the equation is solved to find the effluent biomass concentration

$$D(S_{in} - S) = \frac{D + b_H \cdot X_H}{Y_H} \Leftrightarrow Y_H \cdot D(S_{in} - S) = D + b_H \cdot X_H \Leftrightarrow$$

$$X_H = \frac{Y_H \cdot D(S_{in} - S)}{D + b_H} = \frac{Y_H(S_{in} - S)}{1 + b_H/D}$$

From the equation it is observed that the effluent biomass concentration is a function of substrate removed by the biomass yield and the decay of biomass.

2.4.6 Effluent Inert Organics

To find the inert organics formed in the system, the inert steady state mass balance is simplified and the expression for the effluent biomass concentration is inserted

$$Q\left(X_I + X_{I_{in}}\right) = f_I \cdot b_H \cdot X_H \cdot V \Leftrightarrow D\left(X_I + X_{I_{in}}\right) = f_I \cdot b_H \cdot \frac{Y_H \cdot D(S_{in} - S)}{D + b_H} \Leftrightarrow$$

$$X_I + X_{I_{in}} = f_I \cdot b_H \cdot \frac{Y_H(S_{in} - S)}{D + b_H} \Leftrightarrow$$

$$X_I = X_{I,in} + \frac{f_I \cdot b_H \cdot Y_H(S_{in} - S)}{D + b_H}$$

2.4.7 Effluent Oxygen Concentration

Finally, the steady state oxygen mass balance is solved, the expression for dilution rate is inserted and the equation rearranged

$$\left(O_{2_{in}} - O_2\right) = \left(\frac{1 - Y_H}{Y_H} \cdot \mu + (1 - f_I)b_H\right) \cdot X_H \cdot 1/D$$

$\mu = D + b_H$ is inserted, the equation is rearranged

$$O_2 = O_{2_{in}} - \left(\frac{1 - Y_H}{Y_H} \cdot (D + b_H) + (1 - f_I)b_H\right) \cdot X_H \cdot 1/D$$

The expression for X_H is inserted

$$O_2 = O_{2_{in}} - \left(\frac{1 - Y_H}{Y_H} \cdot (D + b_H) + (1 - f_I)b_H\right) \cdot \frac{Y_H \cdot D(S_{in} - S)}{D + b_H} \cdot 1/D$$

And the equation is simplified to find the effluent oxygen concentration

$$O_2 = O_{2_{in}} - Y_H(S_{in} - S)\left(\frac{1 - Y_H}{Y_H} + \frac{(1 - f_I)b_H}{D + b_H}\right)$$

2.4.8 Solids Sludge Production

The amount of organic particulate matter in the effluent, X_{VSS}, which is a function of the amount of biomass and inert organics in the system may then be estimated

$$X_{VSS} = X_H + X_I$$

From this the total solids sludge production per time unit can be calculated

$$P_{Xvss} = (P_{Xt}) = Q(X_H + X_I)$$

The active fraction of microorganisms, f_{av}, in the sludge is found from the biomass to sludge ratio

$$f_{av} = \frac{X_H}{X_{VSS}}$$

For municipal the typical value of f_{av} is 0.306 for raw unsettled wastewater (Henze, Loosdrecht et al. 2011).

2.4.9 Solids Retention Time

The solids retention time, SRT, is defined by

$$SRT = \frac{mass\ of\ sludge\ in\ reactor}{mass\ of\ sludge\ wasted\ per\ day}$$

For an ideal CFSTR it is assumed that solids and water is equally mixed and from the steady state mass balance, the production of solids in the system equals the solids lost in the effluent. The SRT therefor becomes equal to the hydraulic retention time:

$$SRT = \frac{X_t \cdot V}{X_t + Q} = \frac{V}{Q} = HRT$$

2.5 Oxygen Consumption by Respirometry

As described previously the oxygen consumption by the biomass, is directly linked to the substrate removal and growth of the biomass. The oxygen uptake rate (OUR) of the microorganisms is described combining oxygen consumption for growth and decay using the stoichiometric parameters and process rate expressions presented in Table 3.

Growth Decay

$$OUR = -\frac{1 - Y_H}{Y_H} \cdot \mu \cdot X_H + (1 - f_I) \cdot b_H \cdot X_H$$

OUR represents the amount of oxygen required by the microorganisms and from this the total oxygen demand required in the bioreactor can be calculated (Spanjers 1998).

To evaluate the OUR profile, an aerobic batch test can be run with a predetermined substrate to biomass ratio (F/M ratio) (Çokgör, Sözen et al. 1998). The OUR is measured with a respirometer, where the rate at which the biomass takes up dissolved oxygen (DO) from the liquid is measured. Respirometer techniques are based on measuring the oxygen concentration either in the liquid or gas phase and with or without an input and output of liquid and gas (flowing and static methods), Figure 9 right and left. The method used for the analytical experiment will be based on measuring oxygen in the liquid phase using the Static gas, static liquid method (LSS) (Figure 9 right). For principles on other methods, refer to Spanjers (1998).

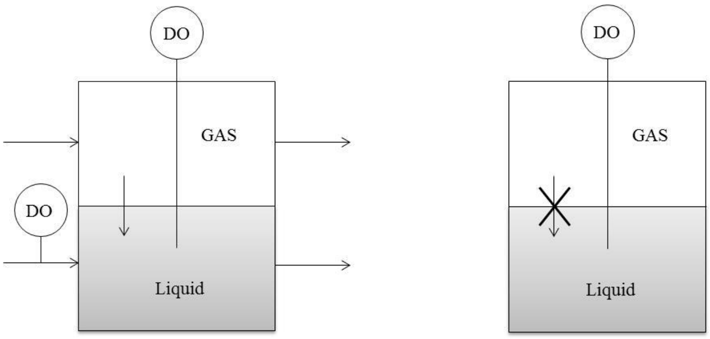

Figure 9: Liquid-phase respirometer; Left: flowing method. Right static (no) gas, static liquid method (Spanjers 1998)

To measure oxygen concentration in the liquid phase a DO mass balance is used over the liquid phase:

$$\frac{d(V_L O_2)}{dt} = Q_{in} \cdot O_{2,in} - Q_{out} \cdot O_2 + V_L \cdot K_L a(O_2^* - O_2) - V_L \cdot OUR$$

Where O_2 = DO concentration in the liquid phase, O^*_2 = saturation DO concentration in the liquid phase, $O_{2,\,in}$ = DO concentration in the liquid phase entering the system, K_La = oxygen mass transfer coefficient (based on liquid volume), Q_{in} = flow rate of the liquid entering the system, Q_{out} = flow rate of the liquid leaving the system, OUR = respiration rate of the biomass in the liquid, V_L = volume of the liquid.

The first two terms of the oxygen mass balance equation describe the liquid transport, and the third term ($V_L \cdot K_La$) describes mass transfer of oxygen from the gas phase to the liquid phase. For the LSS method a closed container with a constant volume is used resulting in no liquid transport or oxygen mass transfer and the first three terms on the right hand side of the equation can be omitted and the mass balance is simplified to

$$\frac{dO_2}{dt} = -OUR\ [mg\ O_2/L \cdot h]$$

To determine the oxygen uptake rate, OUR, only the differential term has to be solved and this is done by measuring decline in oxygen concentration with time due to respiration. This can be approximated using a finite difference term: $\Delta S_O/\Delta t = -\ \mathrm{OUR}$

The specific oxygen consumption rate (SOUR) can be estimated using results from the OUR test and by determining concentration of VSS from the sample used in the OUR test by

$$SOUR = \frac{OUR}{MLVSS}\ [mg\ O_2/g\ VSS \cdot h]$$

The total oxygen demand that needs to be supplied to the bioreactor, FO_c, (mg O_2/d) is then found by

$$FO_c = OUR \cdot V$$

OUR values have previously been estimated for batch reactor tests on the wastewater treated at SART. Values are reported ranging from 140 to 200 mg O_2/L·h (Aulie 2006). Typical values of oxygen demand for municipal wastewater are reported as 6.7 to 6.9 kg O_2/d for raw wastewater with COD concentration of 750 mg/L and with a fraction of active biomass in the sludge of 0.306 mg VSS/mg VSS (Henze, Loosdrecht et al. 2011).

2.6 COD Mass Balance Analysis

COD is considered to be a conservative parameter, and at steady state the COD mass flow out of the system is equal to the COD mass flow into the system (Henze, Loosdrecht et al. 2011).

$$\begin{bmatrix} Mass\ flow\ of \\ COD\ out \\ of\ the\ system \end{bmatrix} = \begin{bmatrix} Mass\ flow\ of \\ COD\ into \\ the\ system \end{bmatrix}$$

For the CFSTR system there is only one inlet and outlet stream and the COD mass balance is described by

$$Q_e \cdot S_{te} + V \cdot OUR = Q_i \cdot S_{ti}$$

Where the first term is the total COD concentration, S_{te}, leaving with the effluent. The second term is the oxygen utilized for degradation of the substrate, FO_c, and the final term is the total COD concentration, S_{ti}, entering the system. The effluent flow, Q_e, equals the influent flow, Q_i. The total effluent COD plus the COD used for respiration, must be equal the total influent COD.

The COD mass balance can be used to check the CFSTR mass balance calculations based on experimental results.

3. SAR AS – SAR Treatment

SAR AS is a company specialized in waste management; offering storage and treatment of waste classified as hazardous waste. According to the Norwegian Environmental Agency (Miljødirektoratet) hazardous waste is waste that cannot be treated together with municipal waste, because it may contain substances that can cause serious pollution or pose a threat to human health and the environment.

SAR AS counts many different locations along the Norwegian coastline from Tananger in the South to Hammerfest in the North along and is also present at international locations. SAR AS receives waste from both onshore and offshore industry, shipping and refineries. Primary source of waste is drilling waste and slops produced offshore, water containing oil and heavy metals and acidic and basic organic and inorganic waste.

This project focuses on the wastewater treatment plant located at Norsea Tananger base, SAR Treatment Tananger (SART), Norway. SART was established in 2002 under a joint ownership between two companies, but today the plant is fully owned and operated by SAR AS. The plant layout is presented in Figure 10.

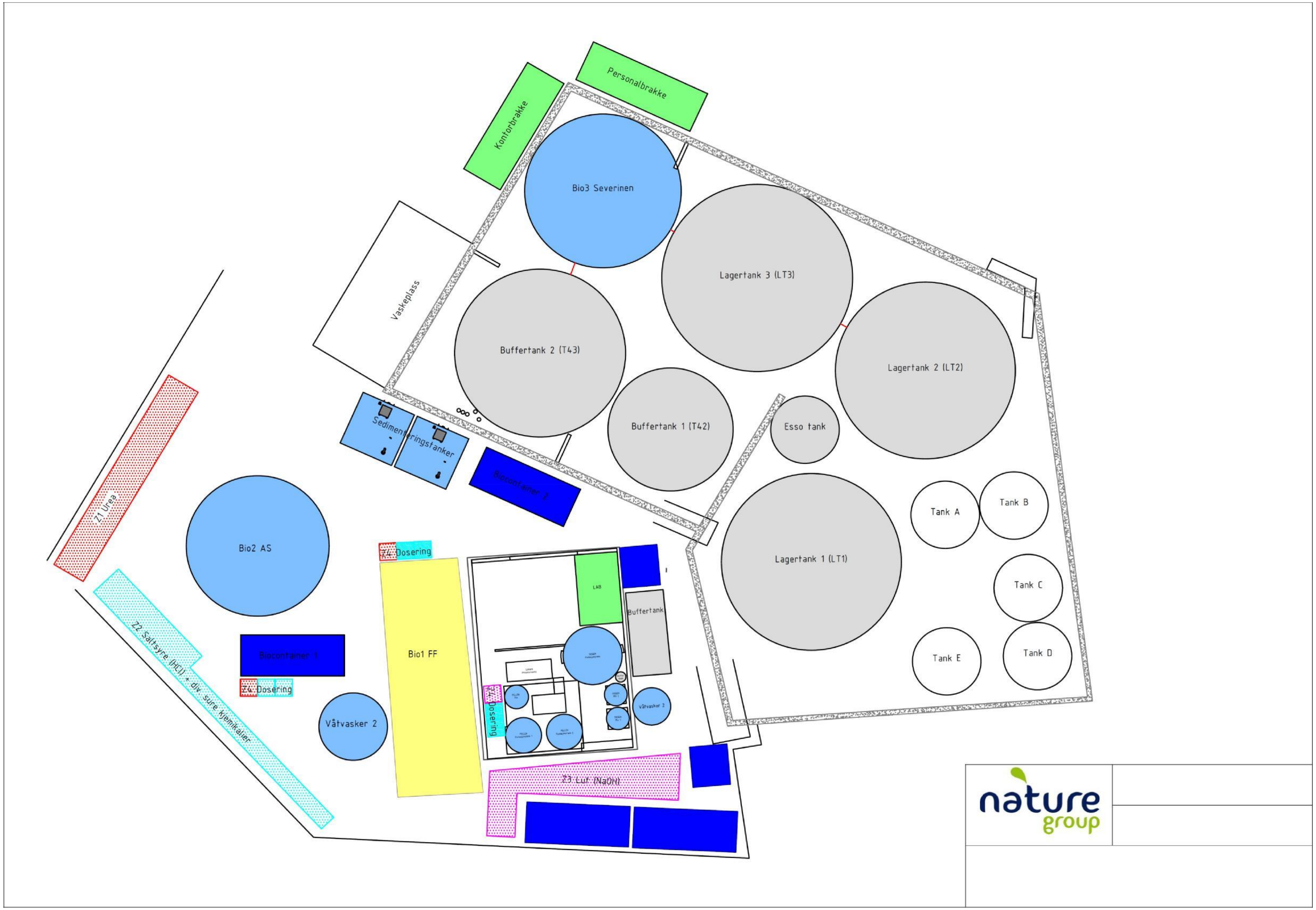

Figure 10: SAR Treatment general arrangement (SART)

3.1 Waste Sources

Knowledge on the type of wastewater treated at SART is limited, some of the components are known, but due to confidentiality from the customer, typically the wastewater composition is unknown (Ali Baig 2015).

The wastewater is often referred to as slop water, which is a term often used for wastewater generated offshore. Slop water is typically contaminated with oil and can also contain other hazardous components dependent on the source. The water is generated in large amount from various onshore and offshore activities. It can originate from offshore drainage water from areas where the water is contaminated with oil, cleaning of tanks or areas that have contained oil, and during drilling and operation of oil and gas production wells generating mixtures of oil and water (miljødepartementet 2004).

SART has a permit to store and treat the following different types of waste (Haug 2015):

- Oil and grease waste
- Oil emulsions, Slop water
- Emulsions containing oil from drilling deck
- Inorganic solutions
- Organic and inorganic acids and bases
- Oil-based drilling fluids
- Water-based drilling fluids containing hazardous compounds
- Process water, washing water

The slop/wastewater treated at SART is discharged to sea following treatment, and components considered to be hazardous and a threat to the environment are subjected to discharge restrictions by the Norwegian Environmental Agency.

3.2 Discharge Regulations

To minimize harmful effects of hazardous waste the Ministry of Climate and Environment in Norway has made regulations on how to handle hazardous waste (miljødepartementet 2004). SART operates according to current Norwegian environmental laws and regulations for discharges to sea from onshore industry. The company has a license to treat up to 100,000 m3/year and to store maximum 3,625 m3 of hazardous waste (Haug 2015).

The components subjected to discharge restrictions are suspended solids, heavy metals, oil residuals, organic compounds and per- and polyfluorinated alkyl substances (PFAS). Table 4 presents the specific components with their respective discharge limits, and a maximum effluent flow rate of 30 m^3/h. Previously the treatment plant discharge limit for total organic carbon (TOC) was 500 mg/L, today the limit is 1000 mg/L (Svendsen 2016).

Table 4: Discharge limits for SART Tananger (Haug 2015)

Discharge component	Discharge limits			
	Concentration (daily mean)		Max annual discharge	
Total Organic Carbon (TOC)	1000	mg/L	50	ton/year
Total Hydrocarbon (THC)	10	mg/L	300	kg/year
Nickel	0.3	mg/L	15	kg/year
Cadmium	0.01	mg/L	0.4	kg/year
Chromium	0.05	mg/L	1.0	kg/year
Arsenic	0.05	mg/L	0.9	kg/year
Lead	0.025	mg/L	1.0	kg/year
Mercury	0.003	mg/L	50	g/year
SUM PFAS[1]	4	µg/L	400	g/year
pH	6-9			
Effluent flow rate (max)	720	m^3/day	100,000	m^3/year

[1] Applies to the compounds PFOS, PFOA, 8:2 FTOH, 6:2 FTS, C9 PFNA, C10PFDA, C11PFUnA, C12PFDoA, C13PFTrA, C14PFTeA, PFHxS, N-Me FOSA, N-Et FOSA, N-Me FOSE, N-Et FOSE.

In addition to the components listed in Table 4, SART also performs analyses for benzene, toluene, ethylbenzene, and xylenes (BTEX), as well as phenol content in the water.

Currently there is an ongoing debate between the industry and the Norwegian Environmental Agency on requirements to new and more stringent discharge restriction to water. Suggestions are concentration limits as low as 10-40 mg/L TOC and 30-120 mg/L COD. In addition to this, requirements for concentrations for total suspended solids of 5-35 mg/L, total nitrogen of 5-30 mg/L and phosphorous of 0.3-3 mg/L are considered (Aanestad 2016).

3.3 Treatment Technology SART

The wastewater treatment plant combines physicochemical treatment with biological treatment. Pretreatment of the water is by chemical precipitation and dissolved air flotation (DAF) for the removal of pollutants affecting the biological treatment, such as suspended solids, oil and grease, heavy metals and toxic organics. Primary treatment is a conventional activated sludge process for the removal of biodegradable matter. The following sections describe the steps of wastewater treatment at SART.

3.3.1 Receiving the waste

Procedure before accepting waste from costumers is to decide whether or not the wastewater is treatable and if it is to be accepted. The sample is analyzed to clarify type of waste, if it is very oily or brine and how it will react when transferred to storage tanks, if it will mix or stratify. Measurements include pH together with specific gravity, TOC, total nitrogen (TN) and finally a jar test is performed on the wastewater sample to see how the water responds to chemical treatment and the quality of the coagulation and flocculation process. Depending on these parameters, it will be determined if the wastewater can be accepted for treatment or not.

If the waste is accepted it is received from ships and trucks. When receiving slops from ships to onshore, the slop is phase separated, where free oil and particulate is separated and the water fraction is transported to SART. The water is stored in tanks and is processed as shown in the process flow chart, Figure 11. The flow chart has been modified and only includes what is in operation today.

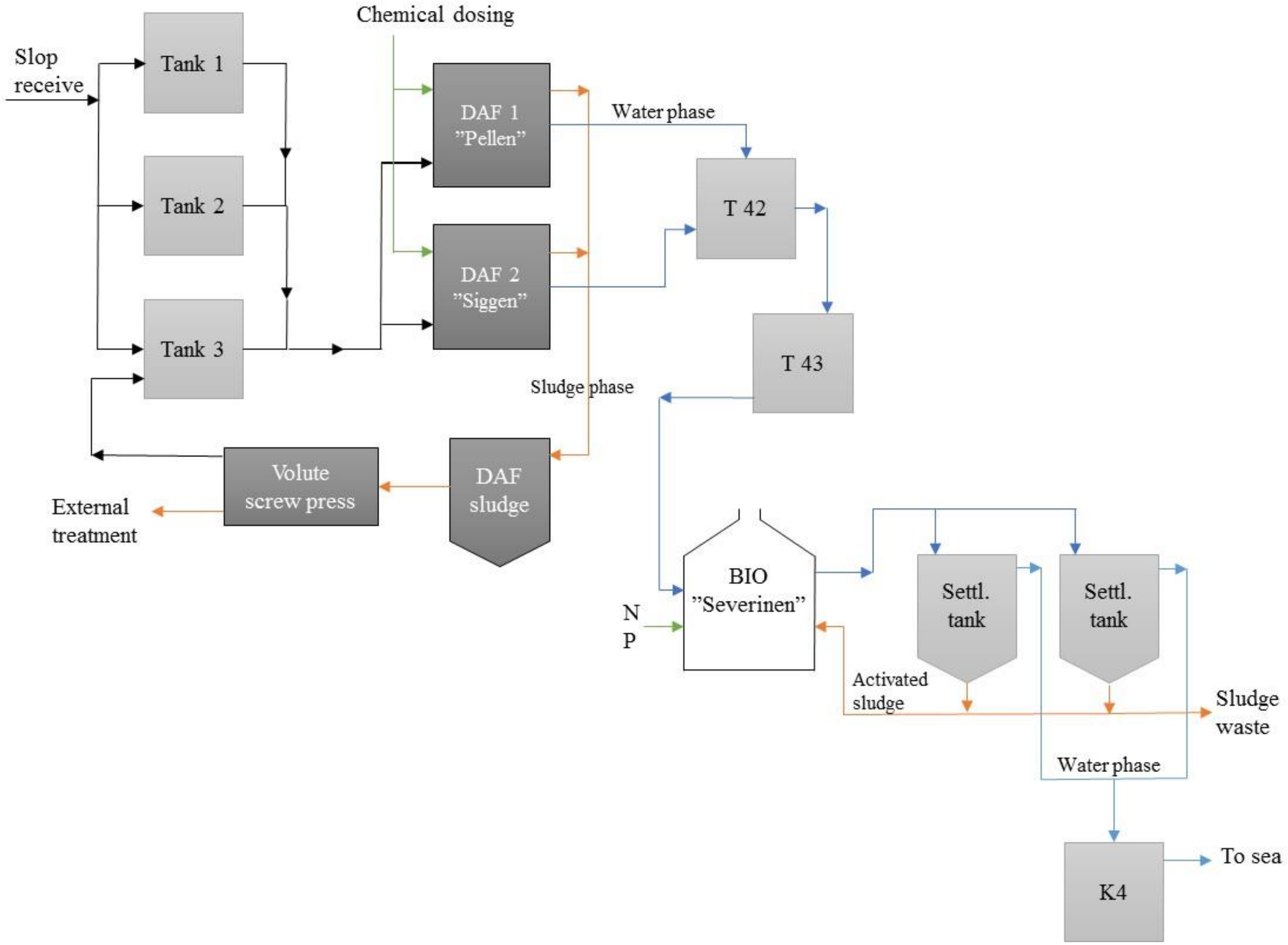

Figure 11: Process flow chart of the wastewater treatment plant, SART

According to the operations manager, previously TOC of received water would vary more and equalization before DAF was necessary. Received water was then stored in one of two storage tanks, one with high TOC and one with low TOC (LT1 and LT2), while flow to process tank LT3 was a mix from the two tanks. Today the TOC of the received waste is much more stable, approximately 5000 mg/L, so there is no need for equalization (Ali Baig 2015).

3.3.2 DAF Systems

Feed from the storage tank passes through a strainer to catch large particles and is pumped for pretreatment made up of two separate DAF systems, DAF Siggen and DAF Pellen, which can be run at the same time or individually (Figure 12). Both systems consist of reactors for addition of chemicals; one reactor with rapid mixing for addition of coagulant and pH adjustment, and another reactor with slow mixing for addition of polymer. Chemicals used are NaOH 25% as base for adjusting pH, precipitant agent (coagulant) is polyaluminium chloride (PAX), and polymer (flocculent) used is Kemira Superfloc 4812rs. DAF Siggen has one flotation chamber and DAF Pellen has two flotation chambers, which can be operated separately or in parallel. Chemical dosing is done according to how treatment is progressing (Mosquera 2016).

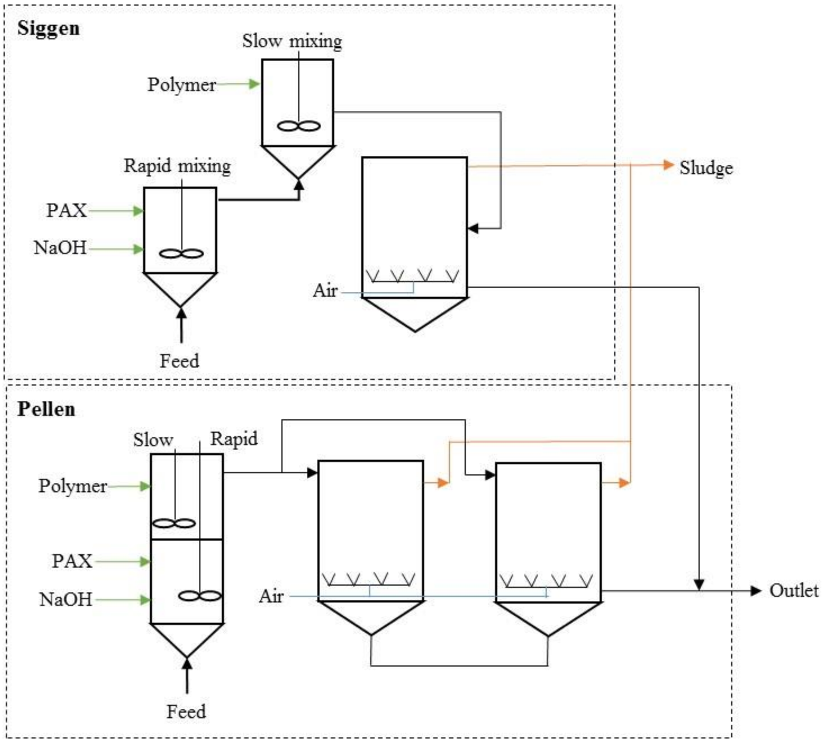

Figure 12: DAF system, DAF Siggen and DAF Pellen

3.3.3 DAF Sludge Handling

Sludge formed in the flotation chamber is skimmed off in the top of the tank and is pumped to a Volute screw press, where polymer is added. In the press sludge is compressed and water is separated out. Excess water from press is pumped back into storage tank LT1 and the dewatered sludge is sent to external treatment. Maximum flow through the press is 3 m3/h and optimal flow will vary, but the press will normally operate without problems at 2 m3/h (SAR 2016).

3.3.4 Biological Treatment

The effluent water from the DAF system is further processed in the activated sludge system, consisting of two biological reactors operating in parallel (AS and Severinen). Today only one of the reactors, Severinen, is in operation. The other reactor has been out of operation since November 2015 due to corrosion. Microorganisms used in the biological reactor are enriched from seawater and have therefore adapted to the saline conditions present in the reactor.

Temperature in the tank should be kept in a range between 35 and 42°C, with an optimal temperature of 40°C. The plant is built with possibility for temperature regulation using a heat exchanger and seawater as coolant, but according to operating personnel, this is not in operation (Svendsen 2016). Urea and phosphoric acid are added to ensure sufficient nutrients; pH is regulated by adding HCl. Optimal concentration of nitrogen should be 75 mg/L, and phosphorous between 2 and 5 mg/L (SAR 2016).

Inlet flow to the bioreactor should be less than 10 m^3/h (this will vary according to TOC concentration). pH should be above 7 and below 8.5, with an optimal pH of 7.2. Optimal concentration of biomass is 20% (SAR 2016). Biomass is regulated with return sludge or retention time. Percentage of biomass is measured visually by sampling manually with a beaker and letting the biomass settle (Mosquera 2016). The aeration system in the tank is a diffused-air aeration system made up of submerged diffusers and blowers. The submerged diffusers (placed at a height of 3 meters above reactor bottom) dissolve atmospheric air into the wastewater by mechanically agitating the water. The oxygen level is measured on-line and should be higher than 1 mg/L, optimally 2 mg/L. According to operating personnel the on-line dissolved oxygen meter is not calibrated and only serves as an indicator. Mixers are installed in the bioreactor to ensure complete mixing in the reactor, but these are currently not working. Since the diffusers are placed at a height of 3 meters, according to the operating personnel it may result in a dead zone in the bottom of the bioreactor due to no mixing.

3.3.5 Settling Tanks

Effluent from the biological reactor is pumped to the two settling tanks run with a continuous flow of $6m^3/h$ for each chamber. Settled sludge is recirculated back to the reactor as activated sludge. According to operating personnel recirculation of sludge has not been done, since there is no need for this (Mosquera 2016). Sludge wasting is designed to be from the settling tanks. According to the operating personnel, sludge is only wasted when the activated sludge is returned to the reactor or for very high TOC or high glycol content (Mosquera 2016, Svendsen 2016). According to the operations manager sludge is not wasted, since the sludge cannot be mixed with the sludge handling from the DAF system (Ali Baig 2015).

3.3.6 Discharge to Sea

The treated water is collected in a tank, K4 – Figure 11, before discharge to sea. At this location, sampling is done to determine concentrations of TOC, pH, heavy metals, BTEX, aromatic compounds, suspended matter, phenol index, and PFAS. These samples are taken from an automatic sampler, collecting samples over a full day, to provide a daily mean value. Determinations are done by a third part, an external laboratory. TOC is also determined daily from grab samples taken from the influent, the bioreactor, and tank K4 for plant-monitoring. These samples are decanted prior to the TOC analysis.

According to the operating personnel, the plant experiences process equipment failures, such as failure of pumps and valves, and downtime in the process. No proper maintenance procedures exist and maintenance is not carried out on a regular basis (Ali Baig 2015). Table 5 summarizes physical data on process equipment at SART.

Table 5: Process equipment SART (SAR 2016)

Treatment stages						
Recieving plant		Tank 1	Tank 2	Tank 3	T42	T43
Buffer volumes (m^3)		1000	1000	1000	300	1000
Physical/chemical treatment		Flotation 1 (Pellen)	Flotation 2 (Siggen)	-	-	-
Volumes (m^3)				-	-	-
Flow (m^3/h)	Range (max)	18-20 (26)	10 (14)	-	-	-
Pressure (bar)		5-6	4-5	-	-	-
Biological treatment		BIO 1 Severinen	BIO 2 AS	Settler 1	Settler 2	-
Volumes (m^3)		800	350	39	39	-
Flow (m^3/h)	Max	10	6	6	6	-
Temp. (°C)	Optimal (range)	40 (35-42)	40 (35-42)	-	-	-
pH	Optimal (range)	7,2 (7-8,5)	7,2 (7-8,5)	-	-	-
DO conc. (mg/L)	Optimal	2 (> 1)	2 (> 1)	-	-	-
Biomass conc. (%)	Optimal	20	20	-	-	-
N conc. (mg/L)	Optimal	75	75	-	-	-
P conc. (mg/L)	Optimal	2-5	2-5	-	-	-
Surface area (m^2)		*	*	-	-	-
Depth		*	*	-	-	-
Sludge handling		Press	-	-	-	-
Flow (m^3/h)	Max	3	-	-	-	-

3.4 Summary of Plant Overview

Main findings, from the plant visits and interviews with operating personnel are:

- Temperature regulation on the bioreactor is not in operation.
- Bioreactor 2, AS, not in operation due to corrosion.
- Mixers not working in bioreactor Severinen.
- On-line dissolved oxygen meter is not calibrated and can only serve as an indication of air flow to the bioreactor.
- Air diffusers are placed at a height of 3 meters, with the likely result of a dead zone in the bottom of the bioreactor due insufficient mixing.
- Recirculation of sludge has not been done and sludge is not wasted from the bioreactor.
- No equalization of the inlet wastewater.
- Maintenance on process equipment is not performed on a regular basis.

4. Material and Methods

Analysis of the biological treatment plant by monitoring the biological reactor was done. Samples of 1 liter were collected by grab sampling over a period of approximately 2 months, with a total of 12 sampling days. Sampling points were from pretreated feed wastewater, biological reactor, and effluent wastewater.

The following determinations were made:

1. pH and temperature for all samples,
2. Salinity on samples from influent, bioreactor and effluent.
3. Mixed liquor dissolved oxygen.
4. Feed wastewater, mixed liquor and effluent TSS and VSS.
5. Total phosphorous and total nitrogen concentrations where determined at the plant.
6. Feed flow rate and temperature were recorded at the plant.
7. Feed wastewater and effluent total and dissolved COD.
8. Total COD on bioreactor samples.
9. OUR analysis.
10. Effluent batch reactor dissolved COD determination.
11. Effluent BOD determination.

4.1 Total Suspended Solids and Volatile Suspended Solids

For TSS determination APHA standard method 2540 D was used.

Homogenized wastewater samples where filtered using a Whatman glass-microfiber filter with diameter 47 mm and pore size 1.2 µm. Due to very high solids content in the samples collected from the biological reactor and the effluent filters would clog and the samples where diluted. Filter plus residual was dried at 105°C until constant weight and TSS of the sample was calculated as the increase in weight.

$$mg\,TSS/L \;= \frac{(m_{filter+residual} - m_{filter})mg \cdot 1000mL/L}{V_{sample}, mL}$$

For VSS determination APHA standard method 2540 E was used.

Filters plus residual was combusted in a muffle oven at 550°C for 40 minutes and volatile suspended organics in the sample was calculated as the weight lost during combustion.

$$mg\,VSS/L = TSS - \frac{(m_{filter+ignited\,residual} - m_{filter} + m_{filter\,loss})mg \cdot 1000mL/L}{V_{sample}, mL}$$

4.2 Chemical Oxygen Demand

For total COD determination the Spectroquant COD Cell Test method 1.14555.0001 was used with a measuring range of 500 – 10,000 mg/L COD. The method corresponds to APHA standard method 5220 D. Standard deviation of the method is ± 31.2 mg/L.

Samples were immediately conserved after sampling using concentrated HCl to a pH between 2 and 3 and were stored at 4°C until analysis was performed. Analysis were performed on the same day as sampling.

The wastewater sample was homogenized and 1 mL of the sample was transferred to a COD reaction cell. The sample was digested in a thermo reactor (Spectroquant TR 620 MERCK) at 148°C for two hours where the water samples were oxidized using a hot sulfuric solution of potassium dichromate ($K_2Cr_2O_7$), with silver sulfate as the catalyst. The concentration of green Cr^{3+} ions was measured photometrically and 1 mol of $K_2Cr_2O_7$ is equivalent to 1.5 mol of O_2 (mg/L O_2 = mg/L COD).

For measuring dissolved COD (CODs) the wastewater was filtered before the analysis using a Whatman glass-microfiber filter with diameter 47 mm and pore size 1.2 µm.

A Spectroquant Pharo 300 MERCK spectrophotometer was used for the analysis.

Note: Concentration of inorganics may interfere with the measurements, especially high concentration of chloride (Cl^-) in saline waters. Samples with a concentration of more than 5000 mg/L Cl^- should be diluted with distilled water prior to the COD determination. Salinity of the samples were measured, with values ranging from 18-30 ppt and samples were diluted 5 to 10 times.

4.3 Total Organic Carbon and Total Nitrogen

TOC and TN determinations are done at the plant using an Analytik Jena multi N/C 2100 TOC/TN analyzer, using the combustion/ non-dispersive infrared (NDIR) method. The method corresponds to APHA standard method 5310 B. Prior to analysis inorganic carbon in the sample is converted into CO_2 by acidification. The CO_2 is then removed by purging before injection into the analyzer (StandardMethods 2005).

4.4 Total Phosphorous

Total dissolved phosphorous is determined by colorimetric method at the plant.

Samples are centrifuged to remove main part of solids, and the samples are then filtrated using a standard glass-microfiber filter with pore size 0.45 µm.

4.5 pH

pH was measured on all samples collected from the plant using a VWR International pH 100 pH-meter.

4.6 Salinity

Salinity and conductivity were measured on some of the samples using a portable MU 6100 L meter with a pHenomenal CO 11 conductivity measuring cell.

4.7 Dissolved Oxygen

According to operating personnel the on-line dissolved oxygen meter measuring on the biological reactor was not calibrated. Very large fluctuations in the on-line measurements were observed during the sampling program, ranging from 0 to 20 mg/L DO. Therefore, handheld measurements of DO concentration were performed while sampling from the bottom of the tank. Since the mixers in the tank were not operating, a few measurements on the top of the tank was also performed for comparison. Measurements were done two to three times, to find an average.

The measurements on the top of the tank, have the highest accuracy, since it was possible to lower the oxygen probe down into the MLSS of the bioreactor. For the bottom measurements, sampling was performed from a valve outlet, where a container was filled to overflow while measuring with the oxygen probe lowered into the suspension.

DO was determined on samples collected from the biological reactor using a portable MU 6100 L meter with a pHenomenal OXY 11 DO sensor. Due to the high salinity of the wastewater, salinity correction was used when measuring.

4.8 Nitrate

To check if autotrophic biomass was present in the sludge, samples from the reactor during the OUR analysis is drawn, filtered and analyzed for nitrate using the Spectroquant Nitrate Cell Test method 1.14563.0001. Measuring range is for 0.5 – 25.0 mg/L NO_3-N (2.2 – 110.7 NO_3^-). The method corresponds to DIN 38405-9.

Standard deviation of the method is ± 0.13 mg/L NO_3-N.

4.9 Respirometry – Oxygen Uptake Rate Analysis

For the OUR analysis APHA standard method 2710 B was used.

Grab samples from the plant was collected and a known volume of sludge from the bioreactor was transferred to a volumetric cylinder of 2000 mL. The sample was continuously stirred during the entire experiment.

For measuring background OUR, no wastewater was added. The sludge sample was aerated and saturated with oxygen until a concentration of approximately 6-8 mg/L was achieved. A BOD bottle with a volume of 250 mL was filled with the oxygen saturated sample to overflow and an oxygen probe was inserted. The bottle was isolated from air and was continuously stirred, Figure 13. Decrease in oxygen concentration was measured over 15 minutes or until the DO concentration was below 2 mg/L.

For actual OUR measurement, a known volume of wastewater was added to the sludge and the procedure was repeated. Different dilutions of the sludge, and different F/M ratios were tried during the experiments. Volatile suspended solids determination of the sludge and COD determination of the wastewater were done simultaneously.

DO was measured using a portable MU 6100 L meter with a pHenomenal OXY 11 DO sensor.

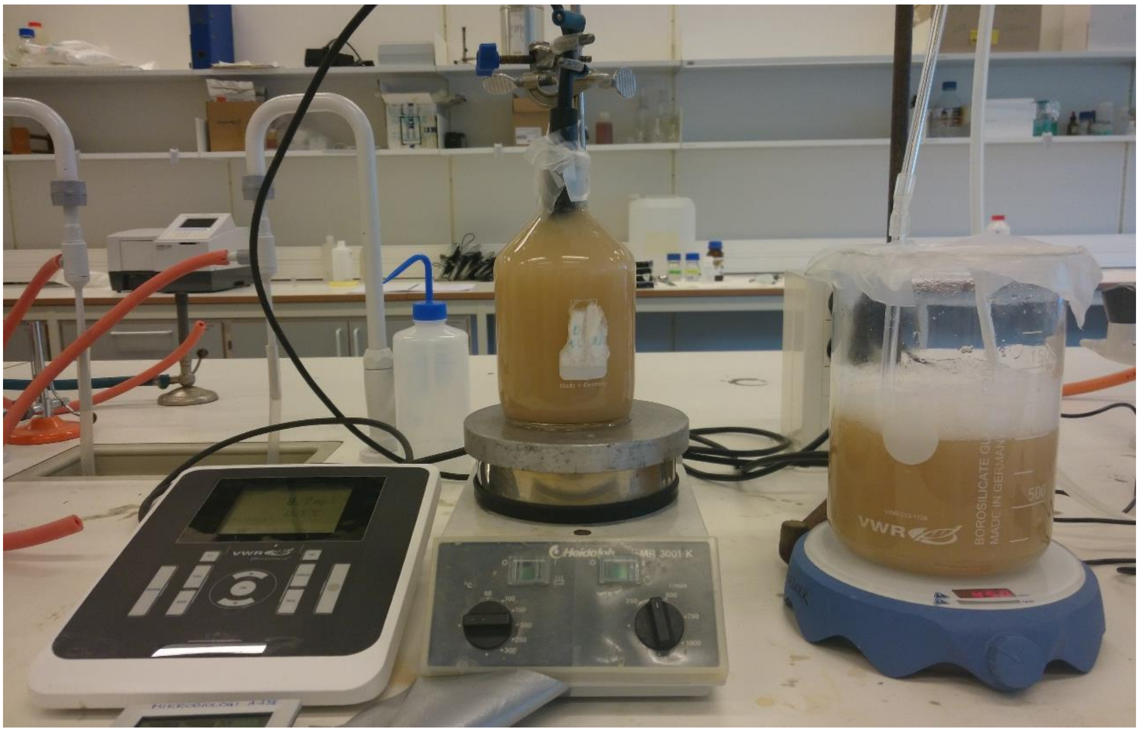

Figure 13: Oxygen uptake rate experimental setup.

4.10 Batch Reactor Test for Effluent CODs Determination

To characterize the COD in the effluent, a batch reactor was run over a period of 20 days until the COD was observed to be constant. Initial and final COD_{total} were determined together with daily determination of $COD_{filtered}$ for 14 days, and then every other day until the experiment was ended, Figure 14.

Grab samples from the plant was collected and 1 liter of effluent together with 50 mL of activated sludge was transferred to a volumetric cylinder of 2000 mL. The sample was continuously stirred and aerated during the entire experiment.

COD determinations were done according to the same procedure described in section 4.2. For dissolved COD the samples were filtered using a VWR glass-microfiber filter with diameter 55 mm and pore size 1.5 µm. (First three days of analysis filters with pore size 1.0 µm were used, this will be reflected in the results)

The Spectroquant COD Cell Test method 1.14895.0001 with a measuring range of 15 – 300 mg/L COD was used. Standard deviation of the method is ± 1.5 mg/L.

Note: Samples with a concentration of more than 2000 mg/L Cl^- should be diluted with distilled water prior to the COD determination. Salinity was measured in the reactor to 18,4 ppt and samples were diluted 5 times prior to analysis.

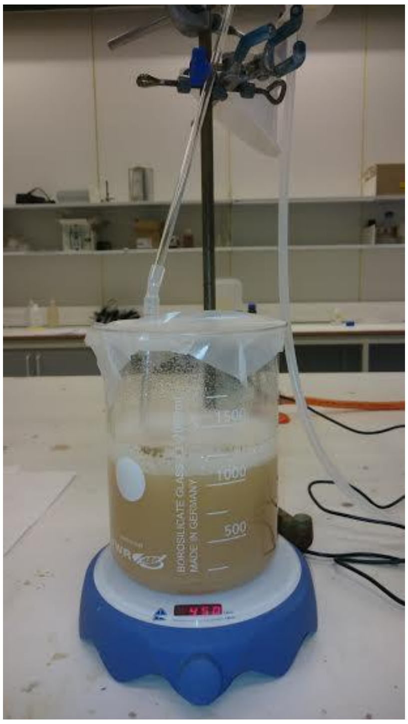

Figure 14: Batch reactor for effluent COD characterization.

4.11 Manometric Respirometer for Effluent BOD Determination

For this analysis a closed system, using a BOD bottle, is used. The method corresponds to APHA standard method 5210 D.

A BOD bottle is partly filled with a known volume of wastewater, leaving a volume of headspace. The headspace gas pressure is measured automatically using WTW OxiTop-C in combination with a WTW Oxitop OC 110 controller over a period of 18 days. The oxygen uptake by the microorganisms is related to the change in pressure in the headspace caused by the oxygen consumption.

Volume of the bottles was 510 mL, filling volume was 330 mL, giving a headspace volume of 180 mL. Effluent wastewater was collected at the plant and diluted to a concentration of 100 mg

COD/L. For a sample of 315 mL, 15 mL of activated sludge was added. During the experiment, the bottles were kept at a constant temperature of 20ºC.

4 determinations were made, with 3 replicates for each experiment:

1. 315 mL raw effluent wastewater with 15 mL of sludge added
2. 315 mL filtered effluent wastewater with 15 mL of sludge added
3. 315 mL tap water with 15 mL of sludge added – blank
4. 330 mL raw effluent wastewater

5. Results and Discussion

The results obtained from the plant visits and interviews, together with the results obtained from experimental analysis are presented and discussed in the following.

5.1 Plant Visit and Interviews

Main finding from SART plant visit and personnel interview was the lack of proper dissolved oxygen measurement in the bioreactor. Additionally, it was suspected that mixing in the bioreactor is not adequate leading to dead zones in the bioreactor. Both findings are considered fundamental for the optimal operation of the wastewater treatment process.

For upgrading the bioreactor, production would need to be stopped and maintenance to be carried out, what would be costly and, this have to weighed against the benefits of upgrading the DO meter and the mixers.

A calibrated DO meter could prevent over and under aeration in the bioreactor, which would result in savings for aeration energy and also improved process control.

5.2 Influent Wastewater

For the first two days of sampling, samples were collected in the morning and in the afternoon, to observe if the concentrations would remain constant over the day. Results are presented in Table 6.

Table 6: TSS, VSS and COD concentrations of influent wastewater samples determined two first days of sampling

Day (time)	TSS (g/L)	VSS (g/L)	COD (mg/L)
1 (08:00)	0.103	0.0375	15730
1 (13:00)	0.157	0.0525	
2 (08:00)	0.099	0.0325	15530
2 (13:00)	0.125	0.0465	17270

An increase of TSS and VSS concentration on both days and an increase of COD concentration on the second day is observed. On the first day only the morning COD determination was usable. Due to the variations seen in the concentrations, the most accurate procedure for sampling would have been to collect samples over the full day during operation, and finally to mix it to represent a mean value for the day.

The results from the analytical determinations of the influent wastewater (after pretreatment) are presented in Table 7. Included are flowrates, TN/TP and TOC concentrations determined at the plant. The average, minimum and maximum value for each parameter has been determined.

Results not determined or available are indicated with “na” in the tables below.

Table 7: Influent wastewater data from period of sampling

Day	Q (m3/h)	Temp (°C)	pH	Salinity (ppt)	TN (mg/L)	TP (mg/L)	TSS (mg/L)	VSS (mg/L)	COD (mg/L)	CODs (mg/L)	P.COD (mg/L)	TOC (mg/L)
1	3	8.84	8.86	na	134	na	103	37.5	15730	15609	121	4540
2	5.5	8.3	8.93	na	143	na	99	32.5	15530	>10000	na	5180
3	6	8.5	8.95	29.9	137	na	226	4.0	16230	14894	1336	5280
4	6.5	10.1	8.90	30.1	515	na	106	39.0	18970	13349	5622	5120
5	na	na	na	na	na	na	na	na	na	na	na	na
6	4.5	10.7	8.83	20.3	117	1.5	310	60.0	15690	10320	5370	3560
7	4.5	10.4	7.25	18.2	97	na	521	90.0	9440	>10000	na	3960
8	6.4	11.7	6.60	20.6	119	na	560	170.0	12180	10770	1410	3690
9	4	8.7	7.71	26.9	89	na	na	na	na	na	na	4210
10	5	9.9	9.21	na	116	2.8	2175	1912.5	14535	10665	3870	3690
11	6.8	9.7	8.30	na	96	na	193	115.3	11025	10400	625	3880
12	6	14.4	7.12	20.5	180.4	na	60	49.9	13700	13367	333	4300
Av	4.85	10.1	8.20	23.8	158.5	2.2	435.4	251.1	14843	12422	2336	4310
Min	0	8.3	6.60	18.2	89	1.5	60.2	4	11025	10320	121	3560
Max	6.8	14.4	9.21	30.1	515	2.8	2175	1912.5	18970	15609	5622	5280

Samples were collected for analysis continuously over 4 days. The operation was shut down due to a high TOC concentration in the bioreactor (1180 mg/L) and samples could not be collected. However, samples during shutdown period (day 5) were collected from the bioreactor to observe any difference. The following characteristics were observed during the 12 days of sampling:

- Temperature of the wastewater is approximately that of the ambient temperature.
- pH does not show large variations compared to the recommended range.
- Salinity is observed to be very high, approaching that of seawater, which was expected.
- Concentration of TN is well above the optimal concentration, given in the operation instruction.
- Concentration of TP seems to be slightly below the optimal concentration, but due to only 2 measurements, this cannot be clarified.
- TSS is observed to be low, which is expected since most suspended solids are removed by pretreatment. TSS determined day 10 is observed to be very high (2175 mg/L) compared to the average value. This increase the average TSS concentration from 224 mg/L to 386 mg/L.
- The amount of organic particulate matter, represented by VSS is low, which was expected.
- COD for day 7 seems to be low compared to the others and the COD_S had a concentration higher than 10,000 mg/L. The COD value (marked in red) has therefore not been included in the average calculation and calculations below. Then COD varies from 11,025 and up to approximately 19,000 mg/L, with an average of 14,800 mg/L.
- COD increase slightly and peaks on the fourth day with approximately 19,000 mg/L.
- CODs from day 2 and 7 (marked in red) were determined with a concentration out of range in the COD test, above 10,000 mg/L, and have not been included in the average calculation.
- Particulate COD (P.COD) is determined from difference in total and dissolved COD.
- P.COD determined day 10 is observed to be very high, 3870 mg/L., which correlates well with the high TSS determined.
- TOC does not show the same peak in concentration on day 4 as the COD.

For the mass balance analysis, it was assumed that the inorganic particulates (FSS) in the system were removed by pretreatment, which fits well with the results from TSS/VSS analysis.

5.2.1 COD, COD_S and TSS Relation

To better observe the correlation between COD, COD_S and TSS, results are plotted in Figure 15.

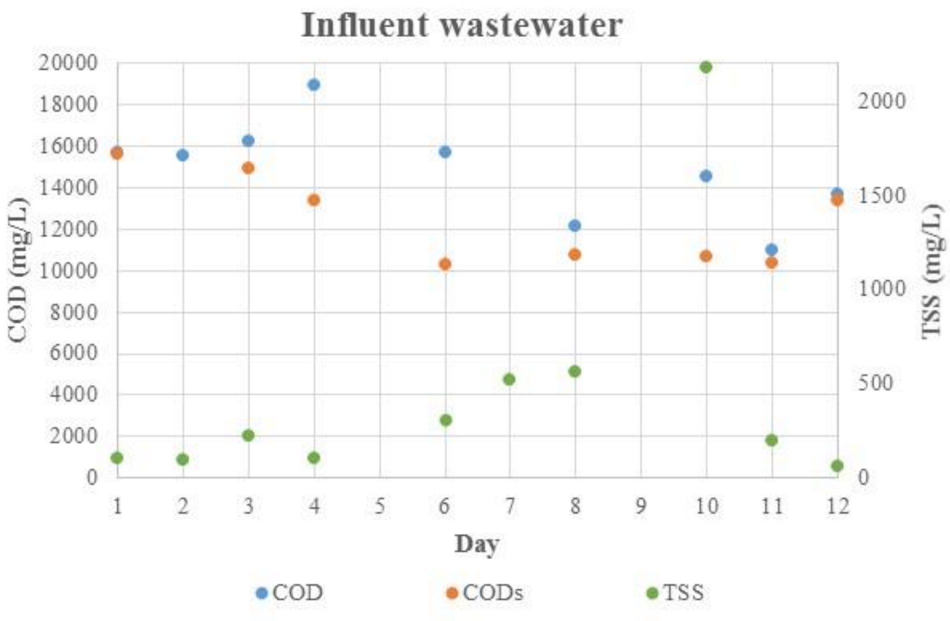

Figure 15: COD, COD$_S$, and TSS determined from influent wastewater samples

- Difference in COD and COD$_S$ (P.COD) is observed to be small, except for days 4, 6 and 10.
- P.COD should correspond to the low TSS concentration, but P.COD is continuously measured well above the concentration of TSS.
- TSS on day 10 is observed to be very high, which correlates with the high P.COD.
- The increase observed in suspended solids concentration from day 7 to day 10 is followed by an increase in COD, but COD$_S$ remains stable.

It is assumed that most of the suspended solids are removed by pretreatment leading to the low TSS concentration. The observed increase in TSS could be due to less effective solids separation from the DAF pretreatment.

The inaccuracy observed in the determinations of particular concentrations could be the result of poor sampling procedure. Samples for COD determinations and TSS/VSS analysis were collected separately, since the samples for COD analysis were conserved with acid. The COD samples were collected in the morning and sometimes the solids content was observed to be high. The explanation from operating personnel was that this was due to upstart of the DAF's, which during start up could flush built up solids into the feed tank, from where the samples were collected. The time difference from collecting samples for COD analysis and samples for TSS/VSS analysis could explain the difference in measured TSS and particulate COD.

5.2.2 Wastewater Treatability

To assess the wastewater in terms of treatability, different ratios have been calculated, results are presented in Table 8. To evaluate the extent of particulate matter biodegradation, VSS/TSS ratios are used. The VSS/TSS ratio is calculated to determine the extent of inorganic particulate matter (FSS), which is expected to accumulate in the sludge of the bioreactor.

Table 8: Relationship between parameters

Day	CODs/COD	VSS/TSS	COD/TOC
1	0.99	0.36	3.5
2	na	0.33	3.0
3	0.92	0.02	3.1
4	0.70	0.37	3.7
5	na	na	na
6	0.66	0.19	4.4
7	na	0.17	na
8	0.88	0.30	3.3
9	na	na	na
10	0.73	0.88	3.9
11	0.94	0.60	2.8
12	0.98	0.83	3.2
Av	0.85	0.41	3.4
Min	0.66	0.02	2.8
Max	0.99	0.88	4.4

- Most of the COD is made up of dissolved COD, indicating high concentration of readily biodegradable COD in the wastewater.
- The VSS/TSS ratio varies, and so far there is no clear relationship between the particulate organic and inorganic solids.
- An average COD/TOC ratio of 3.4 was determined and a maximum of 4.4. This corresponds well with the COD/TOC ratios of the wastewater received at the Mongstad plant (3.3 and 4.2) and also with the calculated theoretical ratios ranging from 3.11 to 4.00.

Notes:

Collection of samples at the plant was performed simultaneously and in accordance with how the operating personnel collected samples for their analysis. A more accurate way of sampling would have been to collect samples over the full day during operation, and finally to mix it to represent a mean value of the influent COD load.

For the effluent wastewater, sampling should have been done from the auto sampler, collecting samples during the day, which would then provide a mean value.

Optimally, the sampling program should have been over 2-3 weeks with no interruption in days.

A prepared standard solution of known COD concentration should have been made prior to analysis to confirm accuracy of the results. This has not been done.

5.2.3 Nutrient requirements

The total fraction of influent biodegradable COD for the wastewater at SART is unknown, but assuming it to be the COD_S determined, the required amount of nitrogen and phosphorous has been calculated. Results have been compared with the concentrations of the influent wastewater to observe if sufficient nutrients are available. Results are presented in Table 9. ΔN and ΔP are calculated as the difference from influent concentration and required concentration.

Table 9: Results from nutrient requirements

day	f_S CODs/COD	$1/(f_S \cdot 0.0826 \cdot Y_H)$	$1/(f_S \cdot 0.0225 * Y_H)$	N required (mg N/L)	P required (mg P/L)	ΔN (mg N/L)	ΔP (mg P/L)
1	0.99	32.97	121.1	477.0	129.9	-343.0	na
2	na	na	na	na	na	na	na
3	0.92	35.66	130.9	455.2	124.0	-318.2	na
4	0.70	46.50	170.7	408.0	111.1	107.0	na
5	na	na	na	na	na	na	na
6	0.66	49.75	182.6	315.4	85.9	-198.4	-84.4
7	na	na	na	na	na	na	na
8	0.88	37.00	135.8	329.2	89.7	-210.2	na
9	na	na	na	na	na	na	na
10	0.73	44.59	163.7	325.9	88.8	-209.9	-86.0
11	0.94	34.69	127.3	317.8	86.6	-221.8	na
12	0.98	33.54	123.1	408.5	111.3	-228.1	na
Av	0.85	39.34	144.41	379.63	103.41	-202.83	-85.20

It is observed that high concentrations of nitrogen and phosphorous are required, this is due to the high COD load of the wastewater. Results show that the influent wastewater is deficient in both nitrogen and phosphorous concentrations, which indicates non optimal conditions for biomass growth and hence organic matter removal.

5.3 Bioreactor Analysis

The results from the analytical determinations of the bioreactor wastewater are presented in Table 10Table 7. Included are flowrates, TN/TP and TOC concentration, together with % biomass determined visually at the plant. The average, minimum and maximum value for each parameter has been determined.

On day 12 of sampling it was decided to try sludge recirculation at the plant, but no wasting of sludge was done (results from day 12 are marked in red).

Table 10: Bioreactor wastewater data from period of sampling

Day	Temp (°C)	pH	Salinity ppt	TN (mg/L)	TP (mg/L)	MLSS (mg/L)	MLVSS (mg/L)	COD (mg/L)	TOC (mg/L)	BM (%)
1	32.5	7.7	na	181	8.6	3900	3902	na	451	20
2	30.7	7.69	na	218	na	3100	3099	7250	495	20
3	30.4	7.72	26.7	132	3	1300	1130	7680	674	20
4	29.6	7.75	28.3	86	5.2	2533	2530	12750	918	20
5	31.3	6.98	29.1	234	11.6	2150	2112	5795	584	20
6	24.5	8.03	23.6	283	2.1	1900	1950	8060	1420	na
7	25.2	7.76	19.6	136	4	3750	3560	9290	702	10
8	27.5	7.54	21.2	163	na	1733	1703	4940	759	10
9	27.3	8.54	28	113	na	na	na	na	990	5
10	28.4	8.37	26.7	54	na	4383	4198	na	673	5
11	29.9	8.2	26.1	65	na	3233	3100	na	629	5
12	39.3	7.86	20.5	173	na	7000	6780	na	1830	30
Av	29.7	7.8	25.0	153	5.8	2965	2906	7966.4	843.8	15
Min	24.5	6.98	19.6	54	2.1	1733	1703	4940	451	5
Max	39.3	8.54	29.1	283	11.6	4383	4198	12750	1830	30

- On day 3 the MLSS suddenly drops by 1800 mg/L, which seems unlikely. This is most likely due to poor analytical determination.
- On day 12 MLSS is observed to be 7000 mg/L, which is well above the average.
- MLSS and MLVSS data points from day 3 and 12 have not been included in the average calculations (marked in red).
- Average MLSS concentration is then 2965 mg/L, which is slightly lower than the recommended range.
- MLVSS concentration is approximately the same as that of MLSS.
- COD was determined one some samples to observe the difference between the concentration in the bioreactor and the effluent concentration.
- A peak in COD concentration is observed on day 4, which corresponds well with the following shutdown of operation.
- The same peak is observed in TOC concentration, though it is still below the limit of 1000 mg/L.
- % of BM is constant for the first 5 days, and then becomes very low compared to recommended value.

It is not possible to relate the measured MLVSS with % BM, except for day 12, where both determinations show very high values compared to the rest. Procedure for measuring % BM is related with a high degree of uncertainty, since it is measured visually

The sudden increase of temperature, MLSS concentration and % BM on day 12, must be due to the recirculation of sludge. Which also leads to a high TOC concentration

5.3.1 pH, Temperature and Salinity

To better observe the variations in pH, temperature and salinity, results are plotted in Figure 16.

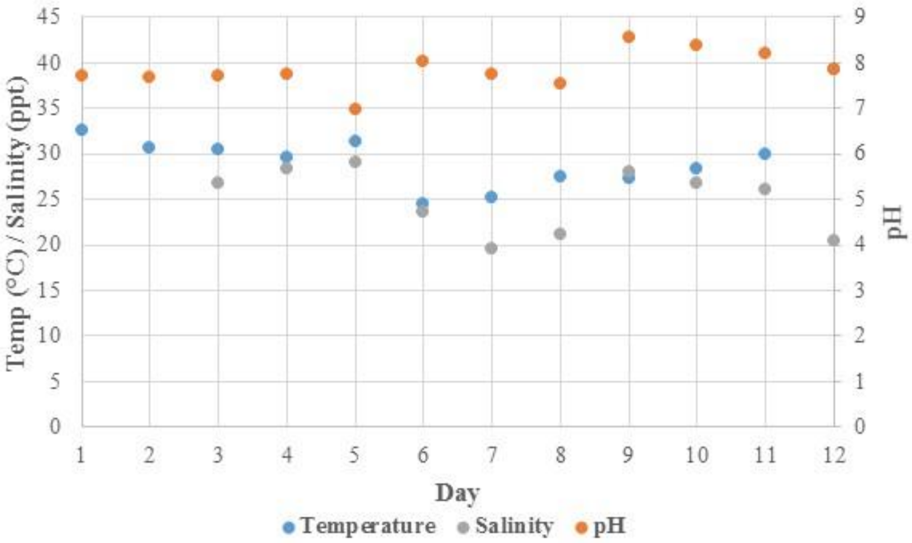

Figure 16: pH, temperature and salinity determined from bioreactor samples

- Average temperature determined is 29.7°C and the temperature varies between 24.5-39.3°C. This is lower than the recommended temperature, which is between 35 to 42°C and with an optimum of 40°C. The high temperature observed on day 12 is at optimum, which is most likely due to the sludge recirculation, and hence is associated with a high microbial activity. During winter time the outside temperature and hence the temperature of the influent wastewater is expected to be much lower, the effects of this has not been discussed in the theory section.
- Salinity only varies slightly, with a maximum concentration of 29.1 ppt, which is below what could affect microorganism growth.
- Average pH observed is 7.8, with a minimum of 6.98 and maximum of 8.54. This is within the recommended range of pH.

5.3.2 Operating Conditions

To observe the operating conditions of the bioreactor, different parameters have been calculated and are presented in Table 11.

Table 11: Operating conditions of the bioreactor

Day	MLVSS/MLSS	F/M ratio (mg COD/mg MLVSS)	VOLR (kg COD/m3·d)	HRT (d)
1	1,00	0,36	1,42	11,1
2	1,00	0,83	2,56	6,1
3	na	na	2,92	5,6
4	1,00	1,46	3,70	5,1
5	0,98	na	na	na
6	1,03	1,09	2,12	7,4
7	0,95	na	na	7,4
8	0,98	1,37	2,34	5,2
9	na	na	na	8,3
10	0,96	0,52	2,18	6,7
11	0,96	0,73	2,25	4,9
12	na	0,36	2,47	5,6
Av	1,0	0,8	2,4	6,7
Min	0,95	0,36	1,42	4,9
Max	1,03	1,46	3,70	11,1

- MLSS is largely made up of MLVSS, hardly any inorganic matter is observed.
- The F/M ratio varies between 0.36 to a maximum of 1.46 mg COD/mg MLVSS. The ratio is observed to be above the typical range for the activated sludge process, except for day 1, 10 and 12.
- The volumetric organic loading rate is observed to be well above the typical range for the activated sludge process.

- The hydraulic retention time, which for the CFSTR process is equal to the solids retention is observed to be in the range from 4.9 to 11.1, varying with the influent flow.

The calculated F/M ratio corresponds well with the high VOLR. Both parameters are very high due to a very high organic load of the influent wastewater.

Increasing the capacity of the plant by increasing the influent flow leads to higher F/M ratio and volumetric organic load. And for the CFSTR process this would eventually dilute the concentration of biomass in the bioreactor, leading to a lower removal of organic matter.

In order to increase the influent flow to the bioreactor while maintaining the rate of organic matter removal, recirculation of the sludge is possible. The F/M ratio can be kept at the same value at an increased volumetric organic load. Recirculating the sludge will result in the solids not being linked to the hydraulic retention time, and the amount of microorganisms in the bioreactor is then controlled by the sludge wasting rate.

5.3.3 Mixed Liquor Dissolved Oxygen

Results from the dissolved oxygen measurements on the bioreactor are presented in Figure 17. Only two measurements were done on the top of the tank, since it was not easily accessible.

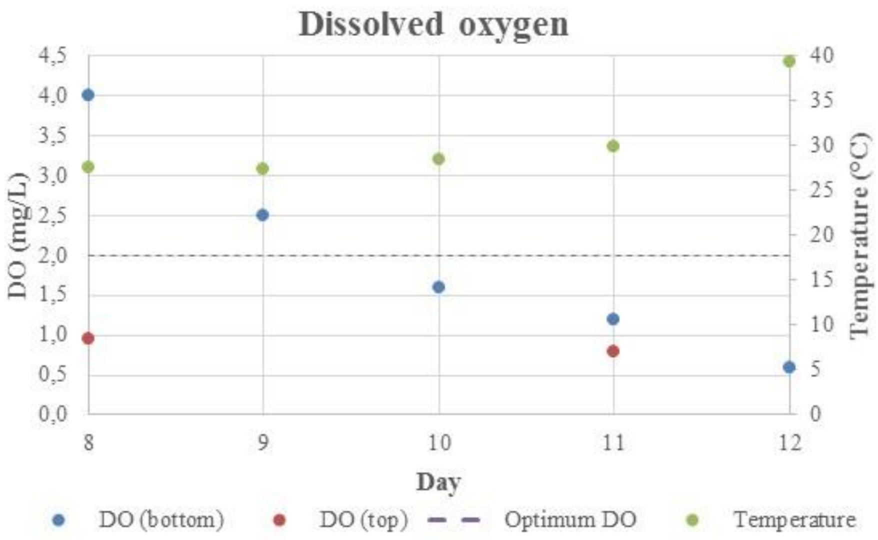

Figure 17: MLSS dissolved oxygen

DO measured in the bottom of the bioreactor, where the diffusers are located is not very constant, dropping from 4.0 to 0.6 mg/L. The results are related with some uncertainty, since the oxygen consumption was rapid and some delay of the oxygen meter is expected. The DO measured at the top of the bioreactor, was below 1.0 mg/L on both measurements with a higher reliability.

The results indicate that the dissolved oxygen concentration in the bioreactor is below the optimal concentration and that mixing in the reactor is not adequate, which was expected.

Due to the inaccuracy of the online DO meter on the bioreactor and with the variations observed in organic load, it will be difficult to target the DO concentration to an optimal concentration.

5.3.4 Respirometry – OUR Analysis

OUR analysis was done using sludge from the bioreactor and influent wastewater to determine the oxygen uptake rate of the microorganisms. Results from the OUR analysis is presented in Table 12.

Table 12: Results from OUR analysis

Day	F/M ratio	OUR_0 (mg O_2/L·h)	MLVSS (g/L)	SOUR (mg O_2/g MLVSS·h)	FO_C (kg O_2/d)
4	7.5	192.6	2.53	76.13	154.08
6	8.0	47.4	1.95	24.31	37.92
7	2.7	212.4	3.56	59.66	169.92
8	1.4	115.2	1.70	67.76	92.16
9	na	19.8	na	na	15.84
10	1.8	252.4	4.20	60.10	201.92
Average	4.28	193.15	3.00	65.91	154.52

Results from day 6 and 9 (marked in red) have been left out of the average calculation, due to very low value. The activity measured on day 6, was observed to be very low, refer to Appendix 1. The amount of biomass is not observed to be extremely low, hence this should not be the reason for low activity.

The activity measured on day 9, was observed to be extremely low and MLVSS was not determined on this day. The reason for these low values in activity for day 6 and 9 is not completely clear. Samples of biomass were collected at the plant in airtight containers, and there may have been some delay prior to the analysis, which could result in some of the microorganisms to die.

The rest of the OUR results show OUR values well above 100 mg O_2/L·h with a maximum for day 10 of 252 mg O_2/L·h. For day 10 the amount of biomass present is also very high, hence the high activity. These values correspond well with what is reported previously, but for exact comparison the SOUR values should be used.

The specific oxygen demand has a calculated average of approximately 66 mg O_2/g MLVSS·h

The required oxygen demand to be supplied to the bioreactor has been calculated with an average of approximately 155 kg O_2/d. This is a very high value compared to the typical value for municipal wastewater. As described previously the oxygen consumption is related to the substrate removal, and the organic load of the wastewater at SART is also very high compared to municipal wastewater.

Plot of OUR measured over time for day 10 has been included to observe the OUR profile, Figure 18.

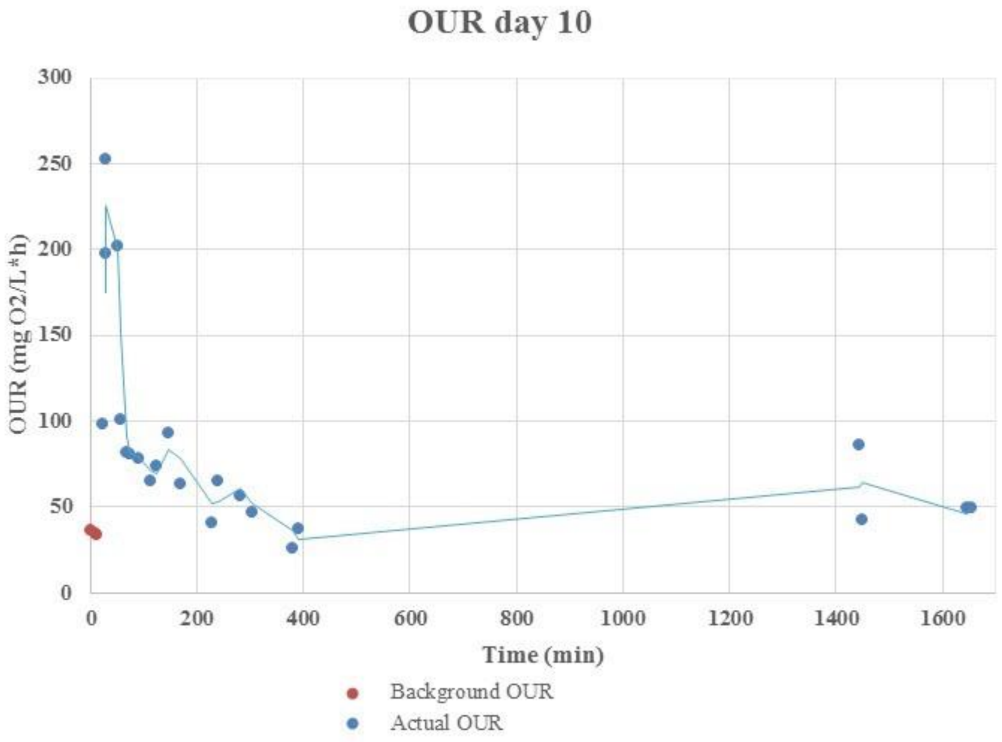

Figure 18: OUR profile from analysis on day 10

Figure 18 shows the background OUR measured on the sludge sample, when no wastewater was added. When adding the wastewater, a rapid increase of activity is measured, reaching a maximum at approximately 250 mg O_2/L·h followed by decrease of the OUR until approximately 6 hours. OUR was measured again the following day and shows no further decrease in OUR. This confirms that the COD in the wastewater is mostly made up of readily biodegradable COD, which also was observed for the COD results previously, Table 8.

Test of OUR for different sludge dilutions and plots used for estimation of OUR are included in Appendix 1.

5.4 Effluent Wastewater

The results from the analytical determinations of the effluent wastewater are presented in Table 13Table 7. Included are flowrates, TN/TP and TOC concentration determined at the plant. The average, minimum and maximum value for each parameter has been determined. Samples was collected for an extra day, to perform effluent batch reactor test and BOD determinations.

Table 13: Effluent wastewater data from period of sampling

Day	Temp (°C)	pH	Salinity ppt	TN (mg/L)	TP (mg/L)	TSS (mg/L)	VSS (mg/L)	COD (mg/L)	CODs (mg/L)	P.COD (mg/L)	TOC (mg/L)
1	**26.6**	**7.85**	na	**81**	na	**1375**	**1374**	>10000	na	na	**474**
2	**31.4**	**7.67**	na	na	na	**3700**	**3700**	**9380**	na	na	na
3	**29.1**	**7.74**	**26.9**	**166**	na	**3200**	**2790**	**8400**	**699.6**	**7700.4**	**500**
4	**29.7**	**7.81**	**28.6**	na	na	**2800**	**2790**	**12815**	**6667**	**6148.3**	na
5	na	na	na	na	na	na	na	na	na	na	na
6	**24.3**	**8**	**27.6**	**230**	**1.6**	**1950**	**1820**	**7570**	na	na	**853**
7	**24.3**	**7.78**	na	na	na	**4200**	**4020**	**8800**	na	na	na
8	**26.3**	**7.48**	**21.2**	**186**	na	**950**	**935**	**4300**	na	na	**778**
9	**28.8**	**8.6**	**27.2**	**253**	na	na	na	na	na	na	**957**
10	**29.9**	**8.25**	na	na	**7.7**	**1350**	**1249**	**4770**	**885**	**3885**	na
11	**23.6**	**8.2**	na	na	na	**383**	**373.3**	>10000	**960**	**9040**	na
12	**34.9**	**7.85**	**20.7**	**173.4**	na	**2975**	**2795**	**4585**	**1800**	**2785**	**1000**
13	na	na	na	na	na	na	na	**6435**	**2450**	**3985**	na
Av	**28.1**	**7.9**	**25.4**	**181.6**	**4.7**	**2288**	**2184.6**	**7914.1**	**2243.5**	**5911.7**	**760.3**
Min	**23.6**	**7.48**	**20.7**	**81**	**1.6**	**383.3**	**373.3**	**4300**	**699.6**	**2785**	**474**
Max	**34.9**	**8.6**	**28.6**	**253**	**7.7**	**4200**	**4020**	**12815**	**6666.7**	**9040**	**1000**

- Temperature, pH and salinity determinations resemble that of the bioreactor.
- pH is observed to be below the discharge limit.
- Total N and P concentrations have not been depleted.
- TSS and VSS concentrations are still high, which was expected due to no sedimentation and sludge removal.
- COD on day 1 and 11 were determined with a concentration out of range in the COD test, above 10,000 mg/L, and have not been included in the average calculation.
- COD are very high due to high P.COD.
- A very high COD and COD_S concentration was determined for day 4, but this corresponds with the high value of the influent on that day and the following stop of operation.
- The COD_S and TOC determinations are very similar and are observed to be below the discharge limit, Table 4.

The total N determinations are made from decanted samples and the total P determinations are made from filtered samples, and hence does not include the N and P contributions from the particulate biomass. In section 5.2.3, theoretical nutrient requirements to the process were calculated and showed that the influent wastewater was deficient in both nitrogen and phosphorous. Since the effluent wastewater contains nitrogen and phosphorous, the bioreactor should be sufficient in nutrients.

The high concentrations of TSS, VSS and P.COD are the result of high biomass content in the effluent wastewater. The COD_S determinations reflect the actual degradation of the organic matter.

5.4.1 Treatment Performance

In order to evaluate the treatment performance of the wastewater treatment process different parameters have been calculated, results are presented in Table 14.

Table 14: Performance of the wastewater treatment process

Day	CODs/COD	COD/TOC	CODs/TOC	COD removal (%)	CODs removal (%)	TOC removal (%)	SS removal (%)
1	na	**21.1**	na	na	na	**89.6**	**64.7**
2	na	na	na	**39.60**	na	na	**-19.4**
3	**0.0833**	**16.8**	**1.4**	**48.24**	**95.3**	**90.5**	**-146.2**
4	**0.5202**	na	na	**32.45**	**50.1**	na	**-10.5**
5	na	na	na	na	na	na	na
6	na	**8.9**	na	**51.75**	na	**76.0**	**-2.6**
7	na	na	na	na	na	na	**-12.0**
8	na	**5.5**	na	**64.70**	na	**78.9**	**45.2**
9	na	na	na	na	na	**77.3**	na
10	**0.1855**	na	na	**67.18**	**91.7**	na	**69.2**
11	**0.0960**	na	na	na	**90.8**	na	**88.1**
12	**0.3926**	**4.6**	**1.8**	**66.53**	**86.5**	**76.7**	**57.5**
13	**0.3807**	na	na	na	na	na	na
Av	**0.2764**	**11.4**	**1.6**	**52.9**	**82.9**	**81.5**	**13.4**
Min	**0.0833**	**4.6**	**1.4**	**32.4**	**50.1**	**76.0**	**-146.2**
Max	**0.5202**	**21.1**	**1.8**	**67.2**	**95.3**	**90.5**	**88.1**

- Most of the COD is made up of particulate COD indicated by the low ratio of total and dissolved COD.
- The COD/TOC ratios are observed to be very high due to the high COD concentrations. Since the TOC is determined from a decanted sample, comparison with the dissolved COD would be more accurate.
- COD$_S$ and TOC concentrations are very similar, hence the low COD$_S$/TOC ratio.
- % COD removal has been calculated, from difference in influent and effluent COD and show low removal percentages.
- % COD$_S$ removed are observed to be very high, except for day 4.
- TOC removal ranges from 76.0% to 90.5%.
- Removal of suspended solids is observed to be low, measurements show higher concentration in the effluent compared to influent for 5 days of sampling.

The low values of COD removal are caused by the high content of biomass in the effluent. The high percentage of COD$_S$ removed indicate that most of the biodegradable COD has been degraded in the bioreactor.

Removal of suspended solids would give an indication of the performance of the sedimentation tank, but since it is not in operation, percentage removal is not very high. The higher concentration observed in the effluent compared to influent could indicate that the system is not in steady state.

Operating the plant as an activated sludge plant, would include operation of the sedimentation tank. This would reduce the concentration of TSS and P.COD in the effluent and a higher COD removal would be achieved. But an increased cost from sludge handling would be expected.

Note: The analytically determined results reflect great variations. In general, variation is observed for all the determinations for the entire sampling program. This must be expected, since the influent wastewater characteristics varies. Additionally, operational adjustment to the process will result in variations.

To obtain more accurate and interpretive results for the wastewater treatment process, the importance of the sampling procedure to be consistent should be emphasized, and sampling should have been done continuously with no interruption of days.

5.4.2 Bioreactor and Effluent SS and COD Comparison

To better observe the difference in bioreactor and effluent suspended solids and COD concentrations, results are plotted in Figure 19 and Figure 20.

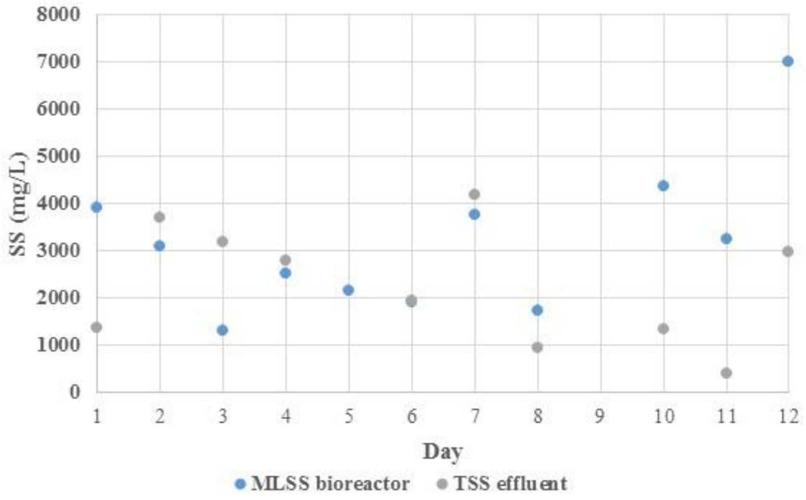

Figure 19: Suspended solids determinations from bioreactor and effluent samples

The effluent suspended solids concentration is observed to be similar to that of the effluent, except for day 1 and 3. When the MLSS decrease or increase, so does the effluent TSS.

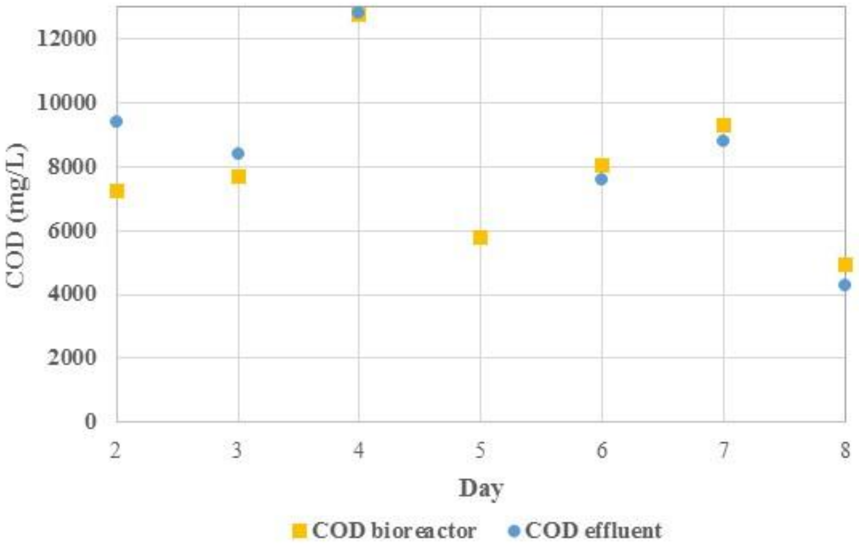

Figure 20: COD determinations from bioreactor and effluent samples

The effluent COD concentration is approximately that of the bioreactor.

Concentration of suspended solids and COD for the bioreactor are observed to be similar for some of the data points, which could be expected since the sedimentation tank is not in operation. Some variations are observed and this could indicate that the system is not in steady state.

5.4.3 Effluent Batch Reactor Test

Results from the COD determinations on the effluent wastewater shows that there is still COD_S left, and to characterize the COD in the effluent a batch reactor test was run. Results from the batch test are presented in Figure 21.

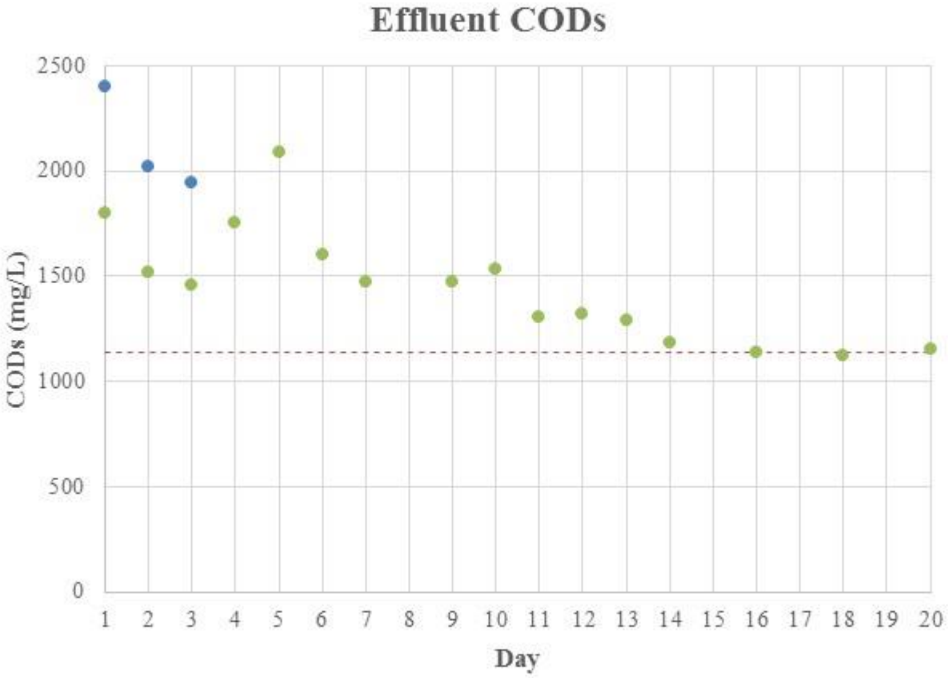

Figure 21: Results from the effluent batch reactor test

For the first three days, filters with smaller pore size (1.0 µm compared to 1.5 µm) were used, therefore a lower concentration of COD_S is observed. To give an estimate on the values, corrections to the three data points were done according to filter pore size difference (data points marked in blue). From this it is also very obvious that the estimate on dissolved COD and hence estimation of readily biodegradable COD, is very dependent on the pore size used.

The dissolved COD decreases until day 16 and becomes constant.

Initial concentrations of COD_{total} and COD_S were determined, and when the COD_S concentration was observed to be constant, the experiment was ended and final COD_{total} and COD_S concentration were determined, results are presented in Table 15.

Table 15: COD concentrations determined from the effluent batch test

	Initial	Final	ΔCOD	% reduction
COD_{total} (mg/L)	4585	1840	2745	60
COD_S (mg/L)	2400	1140[1]	1260	52
$COD_{particulate}$ (mg/L)	2185	700	1485	70

[1] determined from an average of the last three measurements

- Final COD_S, represents the soluble unbiodegradable COD in the effluent sample, $S_{us,e}$.
- Final $COD_{particulate}$, represents the soluble unbiodegradable particulates plus the biomass present in the reactor.
- The concentration of soluble biodegradable COD in the effluent sample, was determined from the difference in initial COD_S and final COD_S concentration, $S_{bs,e}$ = 1260 mg/L.

- A final COD_{total} concentration was observed to be 1840 mg/L, corresponding to a TOC concentration of 526 mg/L when using an average COD/TOC ratio of 3.5.

During the batch test, no nutrients were added; the rate of degradation may have been more rapid if nutrients were added.

The results from the test show that the effluent still contains biodegradable COD, indicating that wastewater treatment process can be further optimized to remove more COD.

5.4.4 Settleability Test

During the batch test, an effluent sample was collected from the plant. The sample was very turbid (left Figure 22) and was left to settle in a measuring beaker while recording time. After half an hour of settling the sludge blanket was observed to be at approximately 75% of the total sample volume, (second picture from the left Figure 22). After 24 hours of settling, the sludge had settled completely and represented approximately 20% of the total sample volume (right Figure 22).

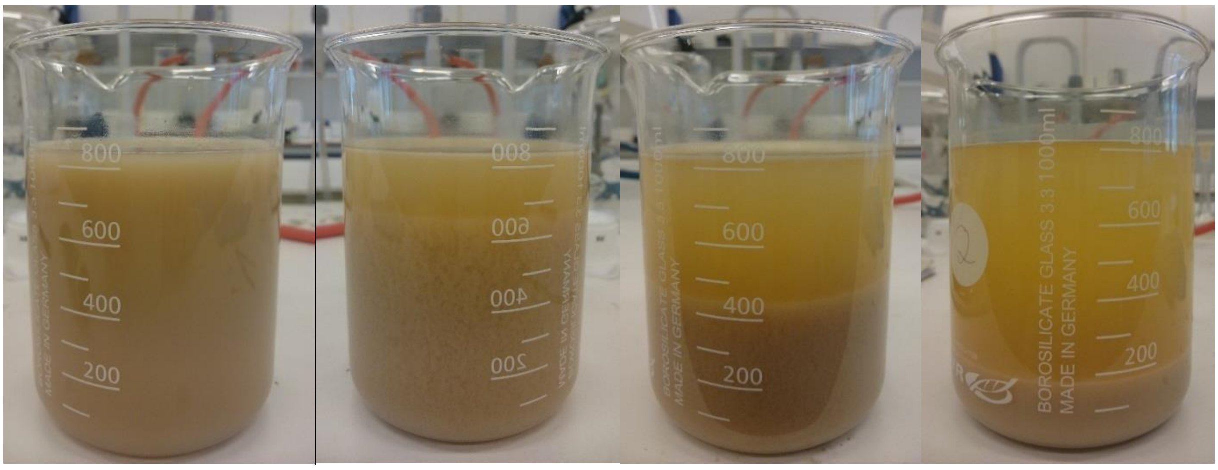

Figure 22: Effluent sample left to settle from the left; 0 hours, half an hour, 3 hours, and 24 hours of settling

Table 16 presents determined sludge volume index, an estimated solids concentration in the recirculated flow and the recycle ratio.

Table 16: Values determined from the settleability test

Parameter	*Value*
TSS (mg/L)	3200
SVI (mL/g)	234.4
$X_{t,r}$ (g/mL)	4267
R	3
Q_r	3·Q

SVI was determined to be 234.4 mL/g, which is a very high value. From this value an $X_{t,r}$ was estimated, which is within the recommended concentration range for the recirculated sludge, but is in the lower end due to the high SVI.

For this specific TSS and $X_{t,r}$ concentration, a recycle ratio of 3 was calculated using the assumption that SRT is high. This would result in a sludge recycle flowrate to be three times as high as the inlet flow, which is very high compared to typical values and seems unrealistic. The SRT assumption cannot be valid.

For an $X_{t,r}$ of 10,000 mg/L, the recycle ratio would be 0.47, which is within the typical range of 25 – 100% of the influent flow.

The SVI test is based on visual observation and is therefore related with errors, which could lead to an overestimate of the index. The test was also done only once, and to get a more accurate result it should be carried out several times.

The reason for the high SVI could also be because the sludge is of the bulking sludge type. The wastewater is characterized as nutrient-limited and also has a high amount of readily biodegradable COD, both factors that could contribute to bulking sludge. To clarify this, the microscopic analysis of the MLSS could be used.

Further analysis of the sludge is recommended in terms of evaluating settleability.

5.4.5 Effluent BOD Analysis

For the effluent BOD analysis, oxygen consumed was measured in 3 replicates for each sample, raw wastewater with sludge added, filtered wastewater with sludge added, a blank sample (tap water with sludge added, and finally a sample of raw wastewater. Results are presented in Figure 23 as an average of the measured BOD results over a duration of 18 days.

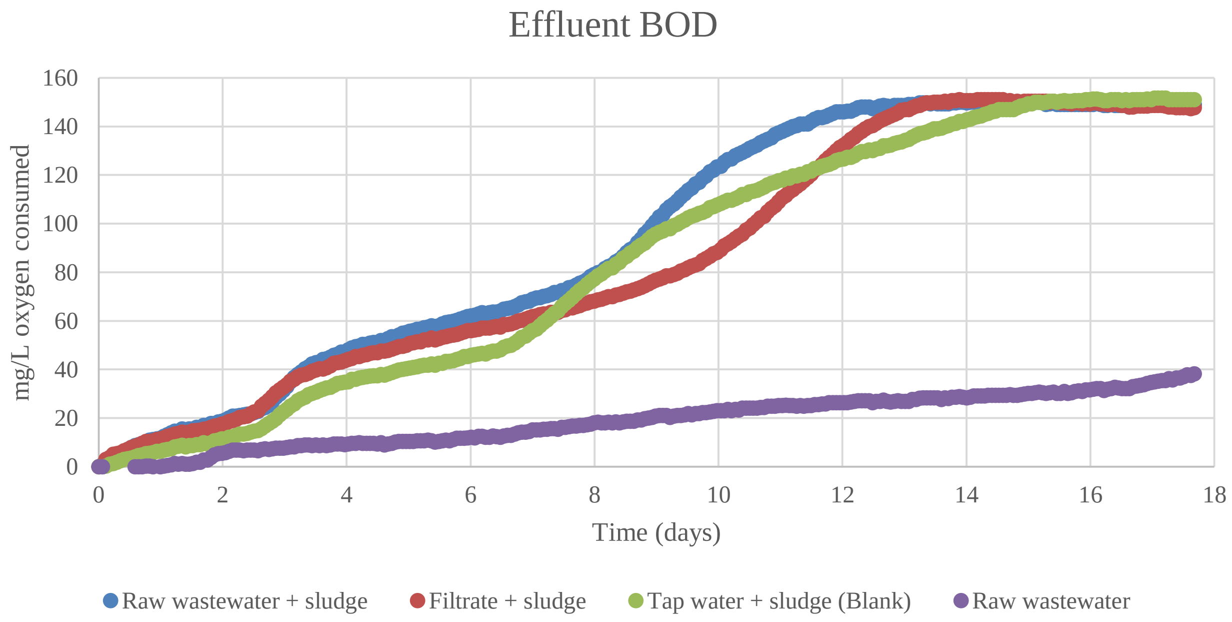

Figure 23: BOD analysis of effluent wastewater collected from SART

The blank sample (tap water + sludge) shows a very high activity, approximately the same as for the raw and filtered wastewater samples. It was expected that the activity in the blank sample would have been much lower and it should have been subtracted from the raw and filtered samples to give the actual oxygen consumption related to BOD in the effluent wastewater.

The effluent sample was diluted to 100 mg/L COD prior to the analysis, but the 15 mL of sludge added was not diluted. The high activity in the blank sample must be due to a high BOD concentration in the sludge added, which also influences the two samples with wastewater. And to get a representative result from the analysis the sludge added should also have been diluted.

5.5 Summary of Main Observations

Influent wastewater:

- Salinity was observed to be very high, approaching that of seawater.
- High particular concentrations were observed, which most likely was due to poor sampling procedure.
- Most of the COD was made up of dissolved COD, indicating high biodegradability of the wastewater.
- An average COD/TOC ratio of 3.4 was determined for the influent wastewater.

Bioreactor samples:

- A sudden increase of temperature, MLSS concentration and % BM was observed when recirculation of sludge was tried.
- Temperature were observed to be lower than the recommended temperature in the bioreactor.
- MLSS was largely made up of MLVSS.
- The F/M ratio varied between 0.36 to a maximum of 1.46 mg COD/mg MLVSS, with some determinations above typical range.
- The volumetric organic loading rate was observed to be well above the typical range.
- Results from mixed liquor dissolved oxygen indicated a DO concentration below optimal as well as inadequate mixing, but determinations were related with some uncertainty.
- Results from the OUR analysis on sludge, showed an average required oxygen demand to be supplied to the bioreactor of approximately 155 kg O_2/d, which is very high due to high organic load of the influent wastewater.
- OUR analysis confirmed high concentration of readily biodegradable COD in the wastewater.
- Results from nutrient requirement analysis showed that the wastewater is deficient in both nitrogen and phosphorous concentrations, which indicates non optimal conditions for biomass growth and hence organic matter removal.

Effluent wastewater:

- High TSS and P.COD concentrations were observed as a result of high biomass content.
- Results showed remaining concentrations of nitrogen and phosphorous, indicating sufficient nutrients added to the bioreactor.
- Remaining COD is primarily made up of particulate COD
- COD/TOC ratios where observed to be very high due to the high COD concentrations.
- A low COD_S/TOC ratio was observed.
- % COD removal showed low removal percentages, with an average of 53%. This was due to high biomass content.
- % COD_S removed were very high, with an average of 83%, indicating that most of the COD from influent has been degraded.
- TOC removal ranges was from 76.0% to 90.5%.
- Removal of suspended solids was low, with an average of 13%. This was due to no operation of sedimentation tank and concentration was observed to be higher in the effluent compared to the bioreactor for several data points.
- The effluent batch reactor test showed that the effluent still contains biodegradable COD, indicating that the treatment process can be optimized further.
- From the effluent settleability test SVI was determined to be 234.4 mL/g, which is a very high value. This was due to very slow settling of the sludge, which could be an indication of bulking sludge.

5.6 Mass balance analysis

From mass balance analysis, the amount of excess sludge generated in the bioreactor, comprising effluent active biomass and inert organics has been calculated, together with the active fraction of biomass. The inorganics from the inlet was calculated assuming a fraction of unbiodegradable particulates of 15% of the total influent COD. Results are presented in Table 17.

Table 17: Results from mass balance analysis

Day	**b_H (1/d)**	**X_H (mgCOD/L)**	**$X_{I,in}$ (mgCOD/L)**	**X_I (mgCOD/L)**	**X_{VSS} (mgCOD/L)**	**PX_{VSS} (kgCOD/d)**	**PX_{VSS} (kgVSS/d)**	**f_{av}**
1	0.34	440.6	2359.5	2611.4	3052.0	219.74	148.48	0.144
2	0.33	764.9	2329.5	2556.1	3321.0	438.37	296.19	0.230
3	0.32	1036.5	2434.5	2713.6	3750.1	540.02	364.88	0.276
4	0.32	869.4	2845.5	3056.7	3926.1	612.47	413.83	0.221
5	0.33							
6	0.27	994.2	2353.5	2655.0	3649.3	394.12	266.30	0.272
7	0.28	77.3						
8	0.30	1143.9	1827	2092.8	3236.6	497.15	335.91	0.353
9	0.30							
10	0.31	1190.7	2180.25	2543.6	3734.3	448.12	302.78	0.319
11	0.32	148.1	1653.75	1688.4	1836.5	299.72	202.51	0.081
12	0.42	1017.4	2055	2408.3	3425.6	493.29	333.30	0.297
Av	0.32	768.3	2226.5	2480.7	3325.7	438.11	296.02	0.264

- It is observed that the sludge generated in the bioreactor is mostly made up of inert organic matter.
- The sludge production varies with the influent COD concentration from 148 kg VSS/d to a maximum of 414 kg VSS/d on day 4, where the COD of the influent was as high as 19,000 mg/L.
- An average sludge production of 296 kg VSS/d was calculated.
- The fraction of active biomass on day 11 is very low, with a value of 0.081 (marked in red) and has not been included in the average calculation.
- The fraction of active biomass then varies from 0.144 to 0.353, with an average of 0.264.

The average fraction of active biomass is observed to be slightly lower than that of municipal wastewater, though some of the calculated values are very similar.

For some of the calculations done, typical coefficients estimated based on municipal wastewater were used. These coefficients should be determined experimentally for this specific wastewater treated at SART to provide accurate results.

To be able to operate the plant as an activated sludge plant, the necessary sludge wasting rate should be estimated. The concentration of solids in the bioreactor is known and sludge from the sedimentation tank can be sampled to determine the solids concentration in the sludge to be recirculated.

Assuming a concentration of solids in the recirculated sludge to be 10,000 mg/L, the sludge wasting flow rate was determined. From the calculated concentration of solids (X_{VSS}), the total amount of solids in the bioreactor was calculated (MX_{VSS}) and the SRT was assumed as the HRT. Results are presented in Table 18.

Table 18: Estimating solids retention time and sludge wasting rate

Day	**MXvss (kg COD)**	**SRT (d)**	**Qw (m^3/h)**
1	2441.61	11.11	0.92
2	2656.77	6.06	1.83
3	3000.10	5.56	2.25
4	3140.88	5.13	2.55
5	na	na	na
6	2919.40	7.41	1.64
7	na	na	na
8	2589.30	5.21	2.07
9	na	na	na
10	2987.47	6.67	1.87
11	1469.20	4.90	1.25
12	2740.51	5.56	2.06
Average	2660.58	6.07	1.83

- Results show that the sludge wasting rate will range from 0.92 to 2.55 m^3/h, with an average of 1.83 m^3/h, for a recirculated sludge with a concentration of 10,000 mg/L.

5.6.1 COD mass balance

To check the data measured in the analytical experiments and the results obtained from the steady state mass balance analysis, a COD mass balance over the system was done. Results are presented in Table 19.

Table 19: COD mass balance results

Day	Fsti (kg COD/d)	Fste (kg COD/d)	FOc (kg O2/d)	ΔCOD Fsti-(Fste+FOc)
1	1132.56	720	na	na
2	2049.96	1238.16	na	na
3	2337.12	1209.6	na	na
4	2959.32	1999.14	154.08	806.10
5	na	na	na	na
6	1694.52	817.56	37.92	839.04
7	1019.52	950.4	169.92	-100.80
8	1870.848	660.48	92.16	1118.21
9	na	na	15.84	na
10	1744.2	572.4	201.92	969.88
11	1799.28	1632	na	na
12	1972.80	660.24	na	na
Av	1858.01	1046.00	111.99	690.41

- OUR was not measured on all days, hence the mass balance can only be calculated for 6 of the days.
- The mass balance does not add up, more COD is observed to enter the system than COD leaving, except for day 7, where the opposite is observed.

For all of the calculation performed in the system mass balance analysis, steady state was assumed, as well as complete mixing in the reactor and constant inlet conditions. The COD mass balance show that the system is not in steady state. Over a longer period, steady state may be achieved.

6. Conclusions and recommendations

The objective of the thesis is to describe the current situation of the wastewater treatment plant, SART and to propose optimizations to the wastewater treatment processes. The wastewater treated at SART was characterized and performance of the biological treatment was evaluated by experimental analysis of the bioreactor and effluent wastewater.

From the plant visit, the main conclusion drawn is:

- For upgrading the bioreactor, the mixing needs to be improved and in order to enhance process control of the plant, the dissolved oxygen meter needs upgrading.

From the experiments and mass balance analysis, the following conclusions are made:

- Most of the COD in the received wastewater is made up of readily biodegradable COD.
- Theoretical estimation of nutrients, showed that influent wastewater is deficient in both nitrogen and phosphorous concentrations. Effluent wastewater has remaining concentration of both, indicating that the bioreactor should be sufficient in nutrients.
- The effluent wastewater has high concentrations of TSS and P.COD as a result of high biomass content.
- The effluent wastewater still contains biodegradable COD, indicating that the treatment process can be optimized further.
- It was not possible to estimate a sludge recirculation rate based on sludge settleability. The sludge settleability needs to be further analysed, to determine if the sludge is bulking sludge. And if so, remedial measures should be determined.
- The performance of the plant shows an average COD removal of 53%, an average COD_S removal of 83% and an average TOC removal of 82%.
- The fraction of active biomass in the sludge is on average 0.264, and an average production of excess sludge in the bioreactor of 296 kg VSS is expected per day.
- According to the objective of the thesis, it is observed that when operating the plant as a CFSTR process, increasing capacity in terms of increased flow is not feasible.

To increase the plant capacity, operating the plant as an activated sludge plant by recirculating and wasting sludge is an option. This would also minimize the high concentration of TSS and P.COD in the effluent, leading to a higher COD removal, but would lead to increased cost in terms of sludge handling.

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Appendices

Appendix 1: Results from the OUR analysis

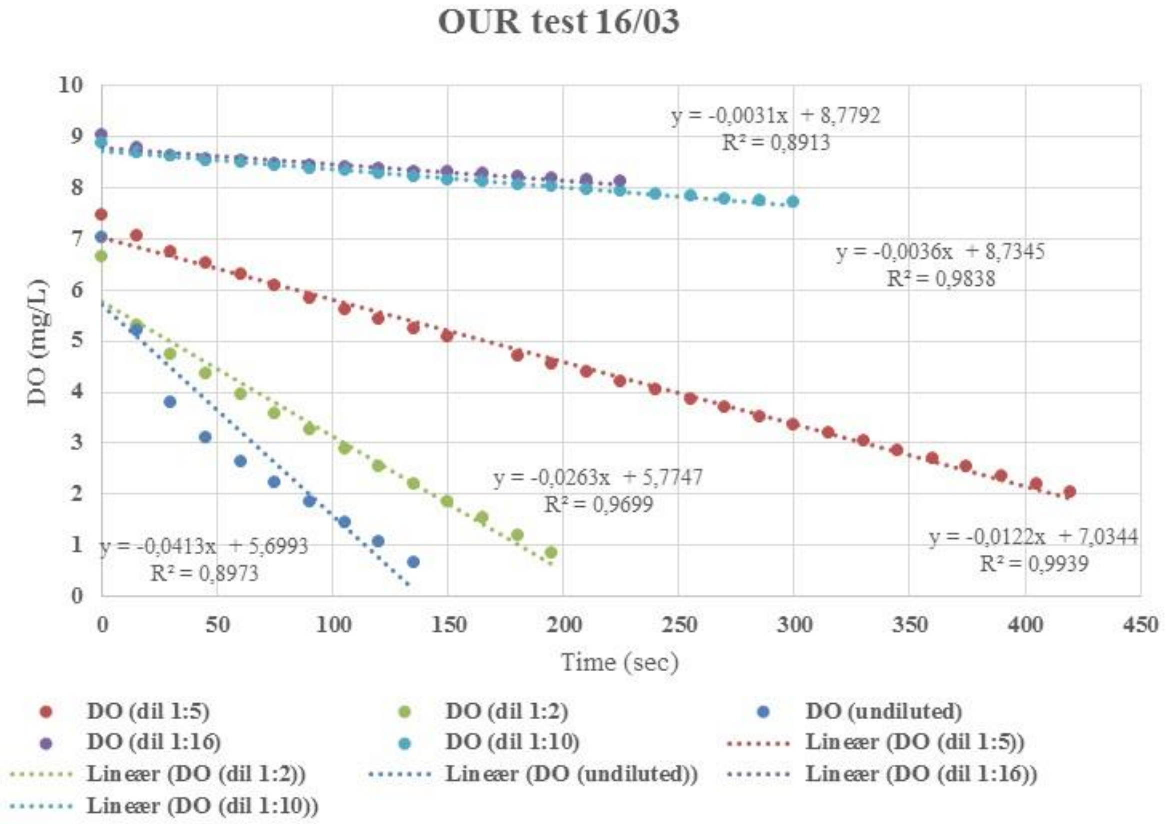

Figure 24: OUR tested for different sludge dilutions

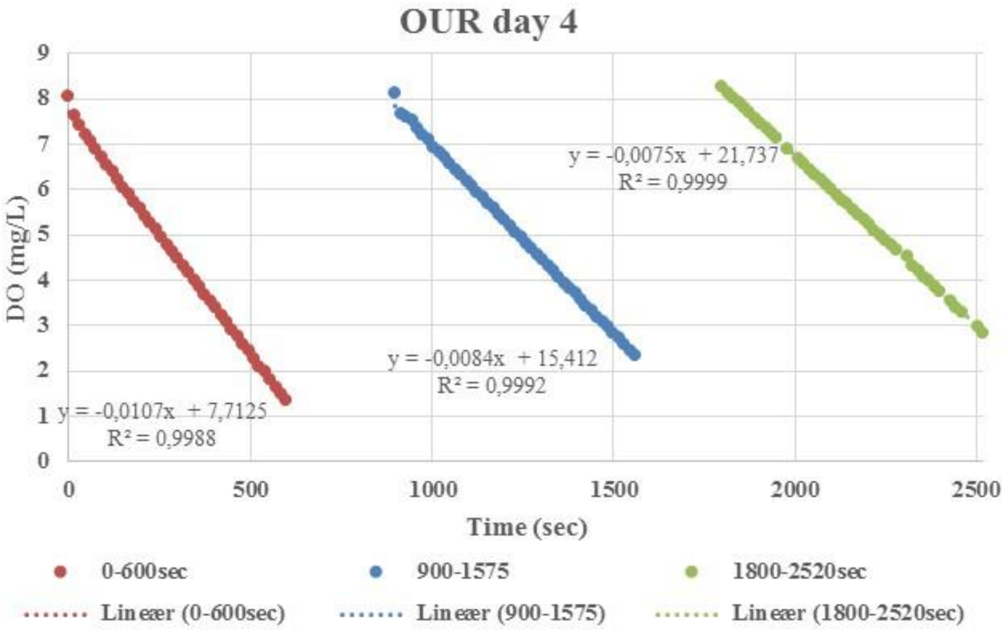

Figure 25: Results from OUR analysis on day 4

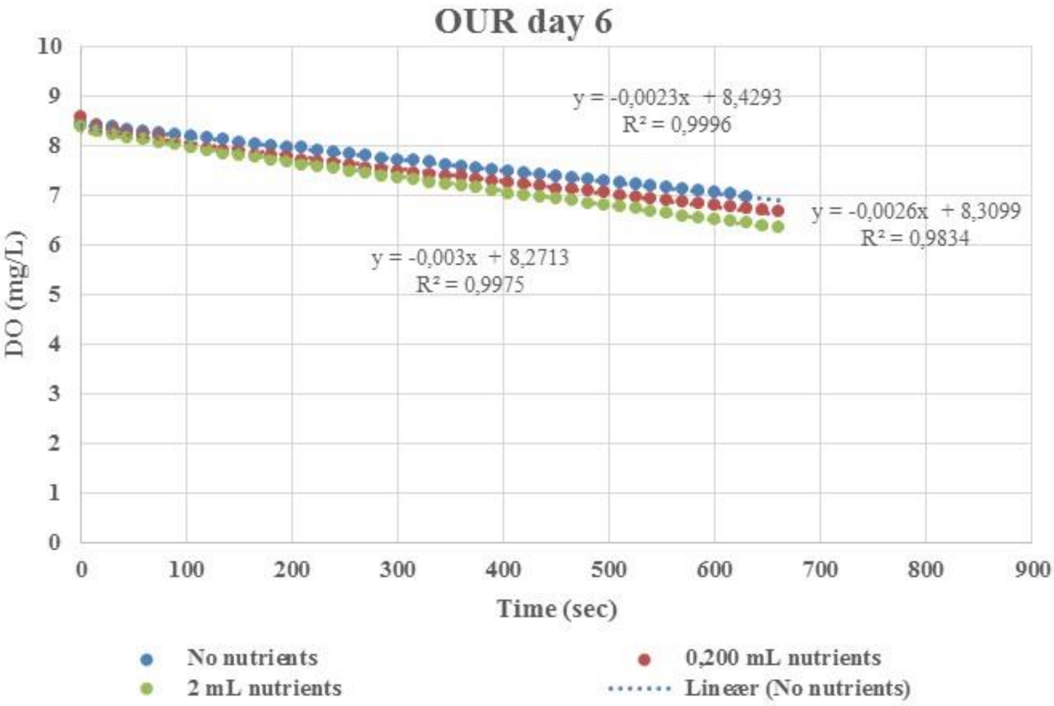

Figure 26: Results from OUR analysis on day 6

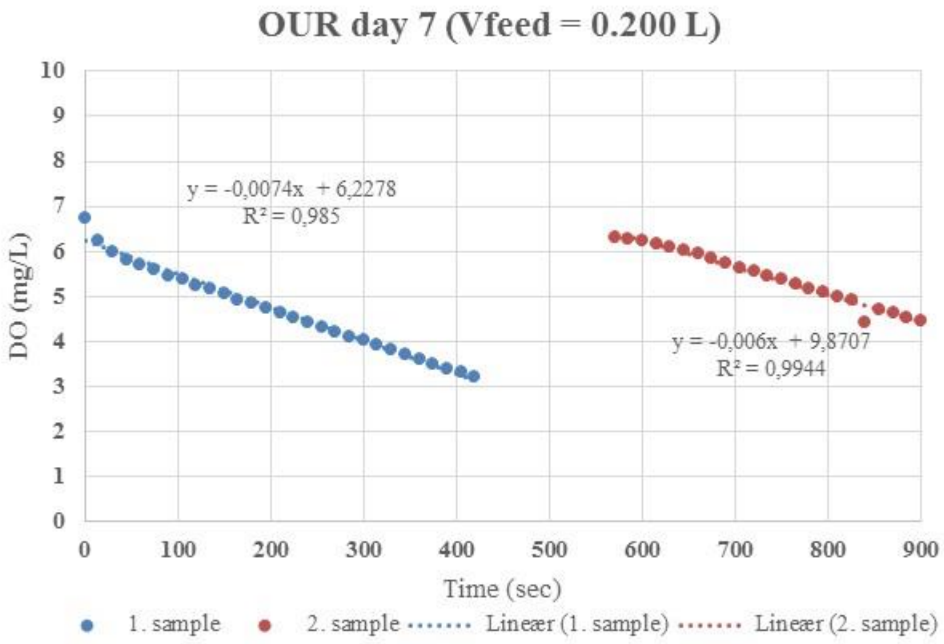

Figure 27: Results from OUR analysis day 7 (feed wastewater volume 0.200 L)

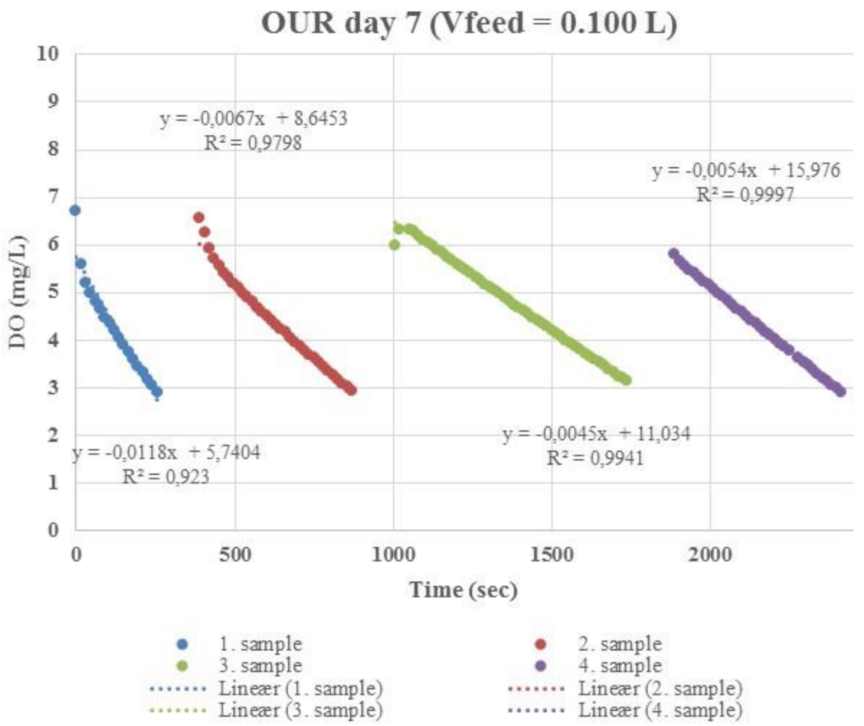

Figure 28: Results from OUR analysis day 7 (feed wastewater volume 0.100 L)

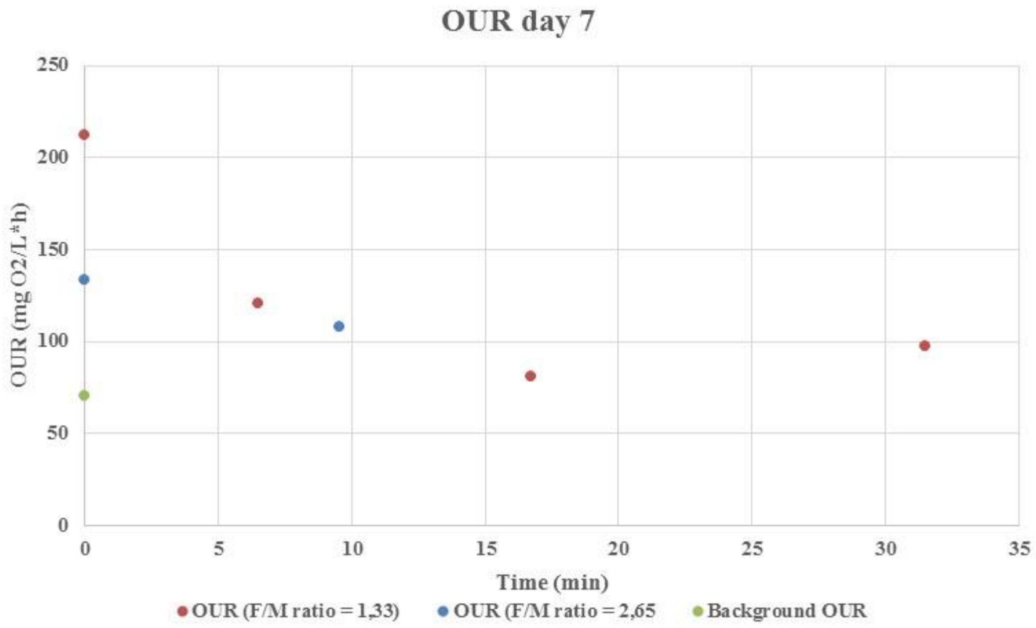

Figure 29: Results from OUR analysis day 7

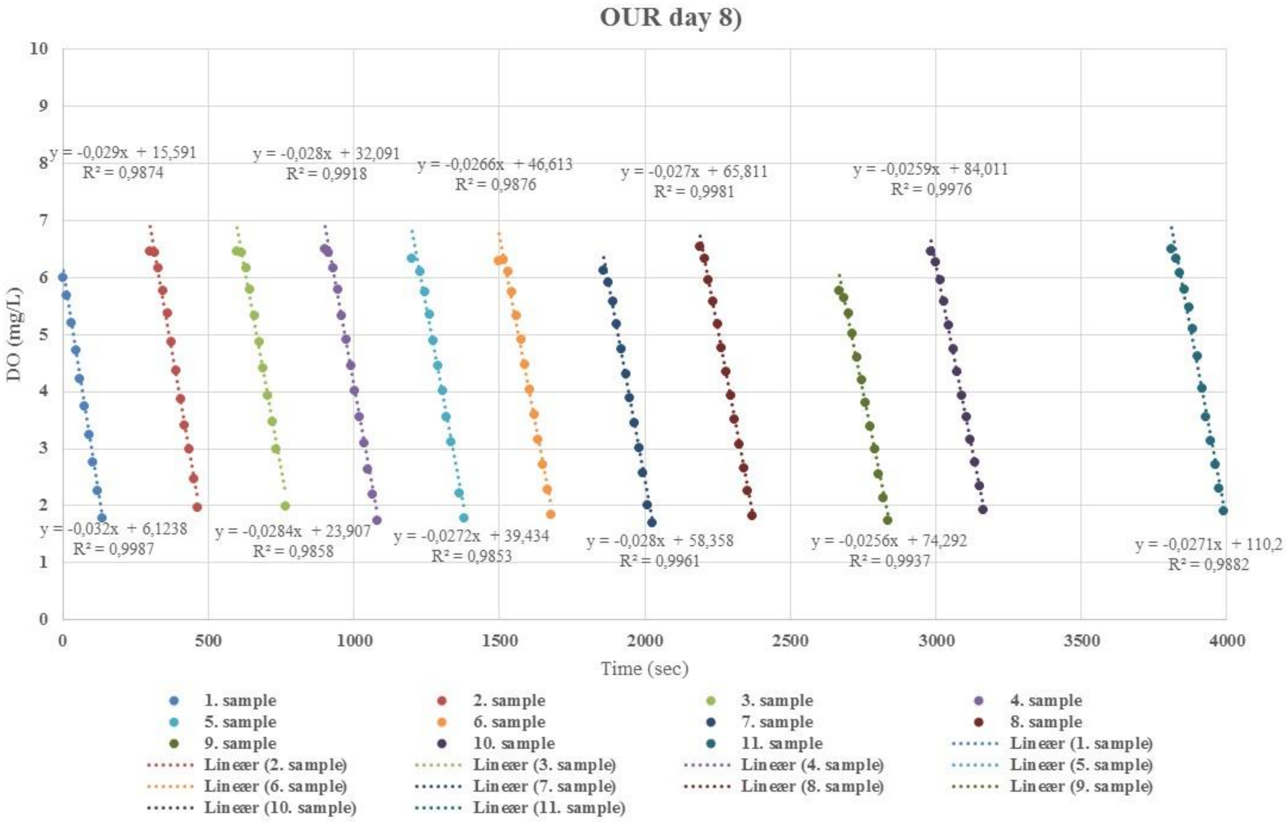

Figure 30: Results from OUR analysis day 8

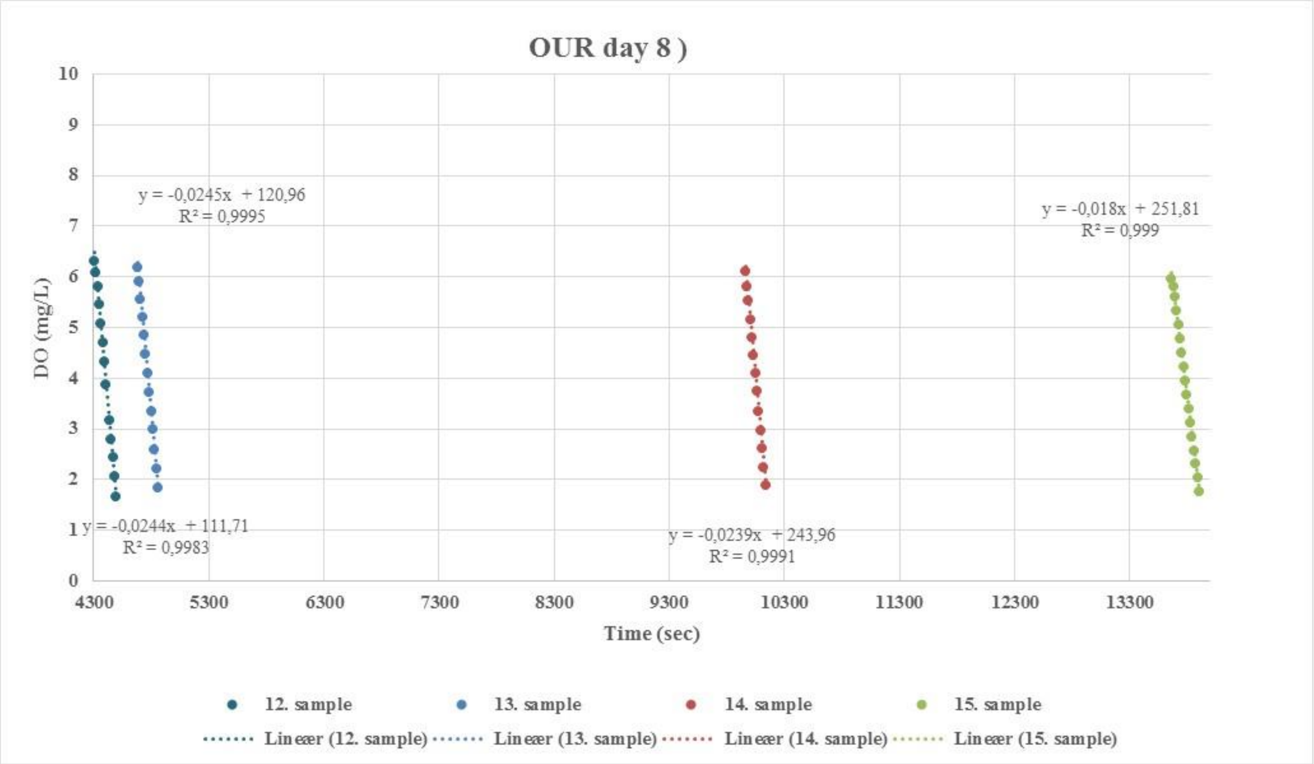

Figure 31: Results from OUR analysis day 8

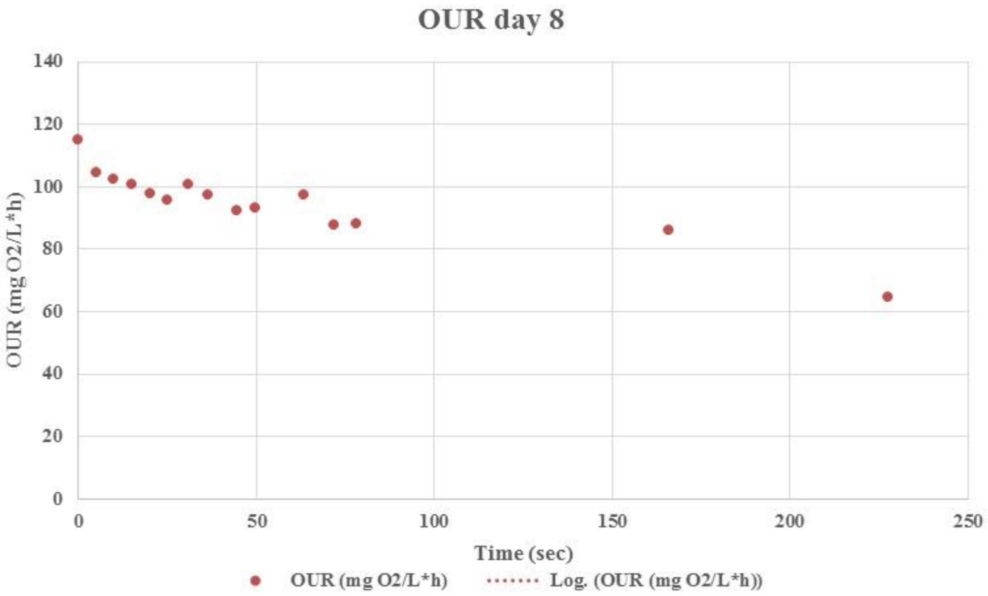

Figure 32: Results from OUR analysis day 8

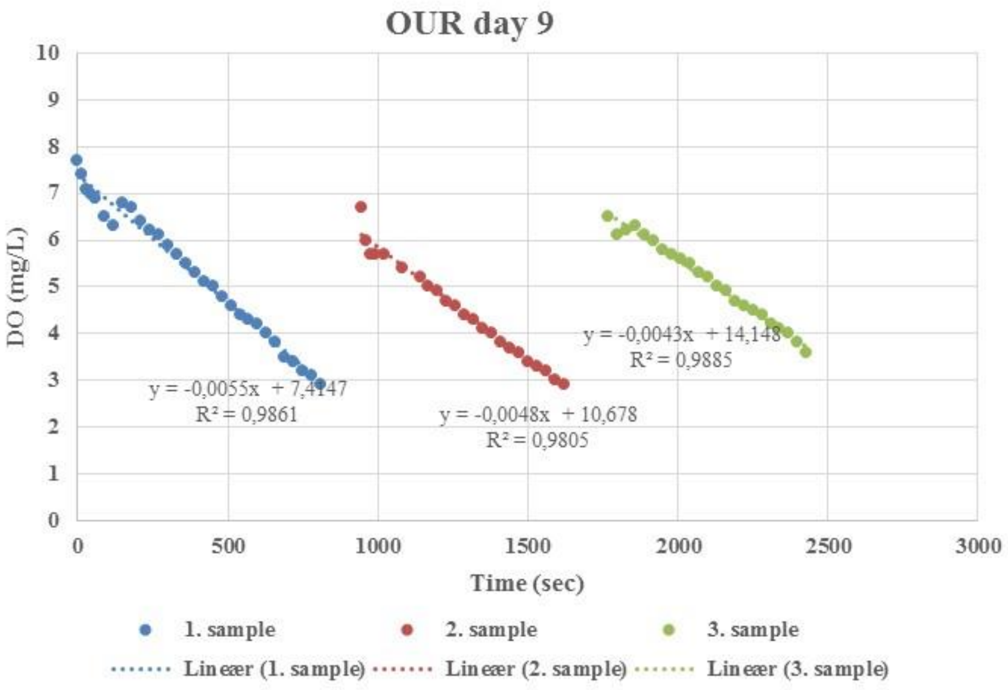

Figure 33: Results from OUR analysis day 9

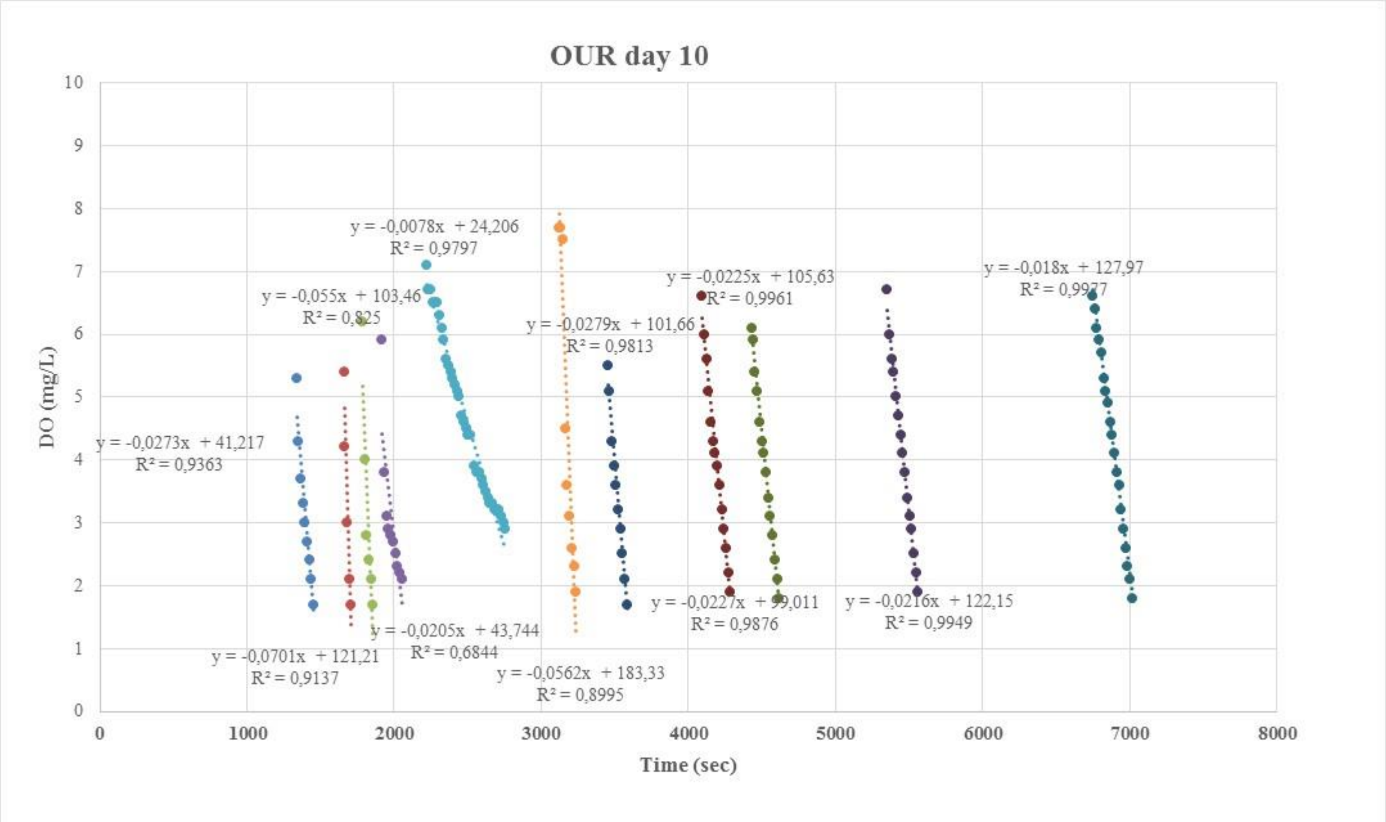

Figure 34: Results from OUR analysis day 10