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Control of the Aeration Process in the Biological Treatment of Wastewater

Internship MSc Applied Mathematics

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Abstract

In this report, the findings of my internship on the biological treatment of wastewater are documented. Environmental hazardous components like nitrogen and phosphorus compounds are removed by bacteria that are located in activated sludge. Some of these bacteria need oxygen in order to break down ammonium, and a human supervisor can control the amount of air supplied to the activated sludge tank by controlling the aerators. A model based controller has been developed to automate the process. We studied how this automated controller can be improved, such that less energy is consumed.

Keywords: aeration, activated sludge model, model based control, wastewater treatment plant

Contents

Preface

As part of the curriculum of the Master Applied Mathematics, every student is required to do an internship of ten to twelve weeks at a company or scientific institute. The main purpose is to work on real life problems in a multidisciplinary team.

I did my internship at Witteveen+Bos, which is an engineering and consultancy firm. Witteveen+Bos was founded by architect W.G. Witteveen (1891-1979) and civil engineer G.S. Bos (1908-2004) in Deventer in 1946. Currently Witteveen+Bos has seven offices in The Netherlands and multiple international offices. In total there are about 1050 employees (January 2018).

Witteveen+Bos operates in four areas: water, infrastructure, environment and construnction. Each area of expertise consists of so-called product-market combinations (PMCs). Each PMC is subdivided into smaller groups. I did my internship in the PMC Digital Technologies. This PMC consists of the following groups: process automation, data science and applications, geo-informatics, business development and asset management. I was working in the process automation group.

I would like to thank Witteveen+Bos for giving me the opportunity to carry out my internship at their company. Besides all my colleagues in the PMC Digital Technologies, I would like to thank my external supervisor Erwin Visser in particular. Thank you for all your guidance, help and suggestions during the project!

Finally, I would also like to thank my supervisors from the Rijksuniversiteit Groningen, prof. dr. H. L. Trentelman and prof. dr. M. K. Camlibel.

Chapter 1

Introduction

The subject of my internship is the biological treatment of wastewater. An important step in the cleaning of wastewater takes place in the so-called activated sludge tank. In this tank, biological reactions take place that remove hazardous and toxic substances from the wastewater. This is done by using activated sludge: sludge containing bacteria that can perform these reactions. The water that leaves the wastewater treatment facility is often called the effluent.

Hazardous substances that need to be removed from the wastewater include nitrogen and phosphorus compounds. There are legal upper bounds for the concentrations of the hazardous substances in the effluent, [1]. After the biological treatment took place, the concentration of ammonium should not exceed 2 mg/L, and the total nitrogen level (the sum of the ammonium and nitrate concentration) should be below 10 mg/L. These requirements have been formalized in the European Water Framework Directive 2000.

As said, to remove these hazardous substances, biological treatment takes place in the activated sludge tank. Roughly speaking there are two different types of zones that can be distinguished in the activated sludge tank: aerated areas and non-aerated areas [2]. In the aerated zones, bacteria use oxygen to transform ammonium into nitrate. In the non-aerated zones bacteria break down the nitrate and produce nitrite, which is then transformed into nitrogen gas. Often the wastewater undergoes these two stages multiple times, by means of recirculation.

As said, the aerobic bacteria need oxygen in order to perform the breakdown of ammonium. Operators at the wastewater treatment plant can control how much oxygen is supplied through the aerators in the tank. On the one hand one wants to put enough oxygen in the tank such that enough biological reactions can take place, on the other hand one does not want to aerate more than absolutely necessary, since aeration consumes a lot of energy. About 60% of the total energy consumption in a wastewater treatmant facility comes from the aeration process [2].

In recent years, there has been a surge in the willingness to improve the energy-efficiency of the wastewater treatment plants. One of the reasons for that was a contract signed by the Dutch water boards and the Ministry of Economic Affairs in 2008. This contract obliged the water boards to improve the energy-efficiency with at least 2% annually, up to at least 30% in 2020. The energy-efficiency can be improved in two ways: either the quality of the treated wastewater is increased, i.e., more waste is removed with the same amount of energy, or the amount of energy that is consumed in the treatment is reduced without deterioration of the effluent quality. Since 60% of the energy consumption stems from the aeration process, it is obvious to try to lower these costs first.

Therefore, Waternet (the water board of Amsterdam) contacted Witteveen+Bos, asking for a solution to the above problem. Together they developed a new control law, that regulates the aeration process in the activated sludge tank. The controller was baptized as WOMBAT® (Witteveen+Bos Optimal Model Based AeraTion).

The WOMBAT® is a model based controller that uses a strongly simplified physical model that describes the relationship between the ammonium concentration and the amount of dissolved oxygen [1]. Based on input measurements (flow, temperature, etc.) an ammonium level is predicted and an optimal oxygen setpoint is calculated based on this predicted ammonium level. The adjective 'optimal' refers to the fact that this is the oxygen setpoint where the total nitrogen level is the lowest, i.e., the sum of the ammonium level and the nitrate level. This means that most of the ammonium is broken down into nitrate and most of the nitrate is broken down into nitrogen gas. The aerators steer towards this optimal oxygen setpoint, and finally the actual ammonium level can be measured and compared with the predicted ammonium level. The difference between the two values serves as feedback.

The WOMBAT® was installed on the wastewater treatment plant Amsterdam Westpoort. WOMBAT® works quite well in practice, especially compared to the original control law. Before WOMBAT® was set in practice, Westpoort made use of a decision matrix.

There were, however, some shortcomings of WOMBAT®. One of the main problems was that the physical model that forms the basis of WOMBAT®, involves a set of parameters that needed to be updated regularly. This had to be done manually, so the WOMBAT® is not very robust. Therefore, the advanced WOMBAT® was developed with the distinctive property that in the advanced WOMBAT® the parameters are updated automatically [3]. In this way, the controller can even cope with sudden drastic changes in the inputs. For example, suppose a sudden large inflow of wastewater due to heavy rain enters the treatment plant, the parameters in the physical model are updated fairly quickly, still yielding an optimal oxygen setpoint and accurate ammonium prediction.

The advanced WOMBAT® thus continuously steers towards the optimal oxygen setpoint, by which we mean that there is optimal removal of total nitrogen. This is, however, not the most energy-efficient oxygen setpoint. Instead of aerating optimally, we can also decide to aerate minimally. By that we mean that a sufficient amount of ammonium is transformed to nitrate, such that the total amount of nitrogen is still within the legal requirements of the Water Framework Directive. In reality this means that we will have aerated less, thus saving energy and money. This minimal oxygen setpoint is referred to as optimal energy oxygen setpoint. In this report, we will study whether it is possible to steer towards this optimal energy oxygen setpoint instead of the optimal oxygen setpoint.

This report is now organized as follows. In Chapter 2 a brief overview of a wastewater treatment plant will be presented. In Chapter 3 we will look into the ASM (Activated Sludge Model), which is one of the most commonly used mathematical models that describe the biological processes in an activated sludge tank. In Chapter 4 we will study the elementary physical model on which the WOMBAT® controllers are based, and we will have a closer look at the design of the advanced WOMBAT®. In Chapter 5 a data analysis will be performed on real life measurements from Westpoort, and we will study whether the physical model on which advanced WOMBAT® is inspired is also present in the actual data. Finally, in Chapter 6, a simulation will be performed with an updated WOMBAT® controller, where we now steer towards a optimal energy oxygen setpoint (as opposed to the optimal oxygen setpoint). Chapter 7 present the conclusion and recommendations of this internship report.

Chapter 2

Wastewater treatment plant

In this chapter a general description of a wastewater treatment plant is given. The incoming wastewater, called the *influent*, is treated in the treatment plant. The outgoing treated water is called the *effluent* [1]. The effluent will become surface water, so it will eventually flow into rivers or lakes. The objective of the wastewater treatment plant is thus not to produce drinking water, since for that there are more severe conditions on the effluent quality.

As said, the influent consists of wastewater. This wastewater can be divided into two parts: wet weather flow and dry weather flow. Wet weather flow consists mainly of rain water (surface run-off), while dry weather flow consist of industrial wastewater and wastewater from households, like flushed toilets, showers, sinks, etc. Sometimes the latter is also referred to as municipal wastewater. Rain water by itself is already clean and does not need much treatment. However, since the sewerage in The Netherlands is a *combined sewer*, the rain water and dry weather flow end up in one pipe entering the treatment facility, and it is cleaned nonetheless. Nowadays, *separated sewers* became more and more popular, and in these type of sewerages the municipal wastewater is separated from the surface run-off.

Roughly speaking, three different stages can be distinguished in the wastewater treatment plant. This is depicted in a schematic overview in Figure 2.1, taken from [2].

First, large objects from the wastewater will be removed using grids. This stage is called the pretreatment. Anything larger than a pea will not pass the grids and will thus be removed from the wastewater. This include for example diapers and branches. The waste will get compressed and transported to an incineration plant where it is burnt.

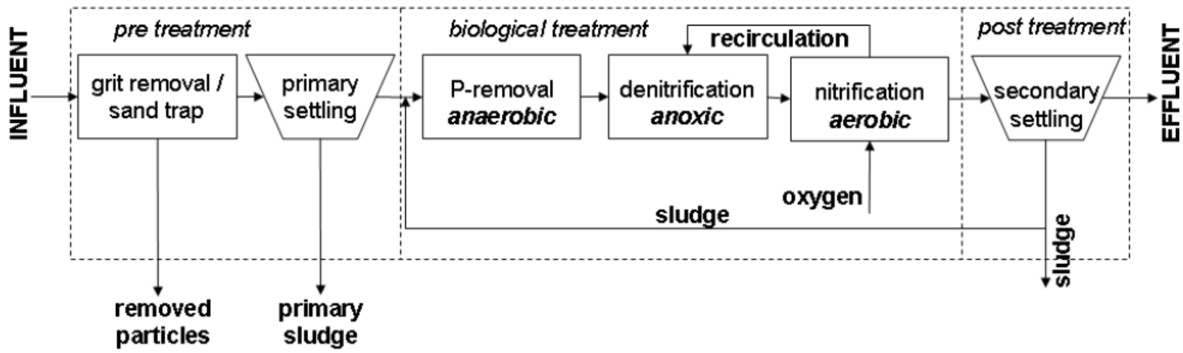


Figure 2.1: Schematic overview of a wastewater treatment plant. The figure is taken from [2].

The water then enters the first tank, sometimes referred to as the pre-settling basin. The water will be stirred slowly, and any heavy substance will sink to the bottom, while anything lighter than water (e.g., oil and grease) will rise to the surface. The heavy layer at the bottom of the tank is called primary sludge and will be removed. The thin layer of oil and grease can be skimmed off, and the remaining water is now already relatively clean. It will now enter the next stage, the biological treatment.

In the biological treatment tank, bacteria and protozoa perform biological reactions to remove hazardous substances from the water. These hazardous substances include ammonium (NH_4), nitrate (NO_3) and phosphor (phosphoric acid, in the form of H_3PO_4). There are two different types of bacteria: heterotrophic and autotrophic bacteria. Heterotrophic bacteria need another living source of energy or organic carbon in order to live. Autotrophic bacteria on the other hand are literally self-feeding organisms, and can produce their own organic compounds [4].

In the biological treatment plant, three different parts can be distinguished: the aerobic zone, the anoxic zone and the anaerobic zone. The bacteria that perform reactions in the aerobic zone need oxygen in order to live. They are thus heterotrophic bacteria. These bacteria break down ammonium (NH_4) into nitrate (NO_3). This reaction is called nitrification:

$$2O_2 + NH_4^+ \rightarrow NO_3^- + H_2O + 2H^+. \tag{2.1}$$

On top of that, also almost any organic compound will be oxidized. So not only oxygen will be used for nitrification, but it can also be used to break down organic matter. For example, consider the breakdown of ethanol, C_2H_5OH:

$$C_2H_5OH + 3O_2 \rightarrow 2CO_2 + 3H_2O. \tag{2.2}$$

Similar equations hold for the other organic compounds. In general there is far from enough oxygen to perform the breakdown of all organic compounds. The *Chemical Oxygen Demand*

(COD) is used as a measure for the total amount of oxygen needed, in order to fulfill all chemical or biological reactions that require oxygen [4].

The nitrate that is a product of the nitrification process in the aerobic zone, will be broken down into nitrogen gas (N_2) in the anoxic zone:

$$4NO_3^- + 4H^+ \rightarrow 2N_2 + 5O_2 + 2H_2O. \tag{2.3}$$

This reaction is often called denitrification. Nitrogen gas will leave the biological tank as bubbles. Note that a product of denitrification is oxygen, and this oxygen is directly used to transform some organic compound into CO_2 and H_2O, like in reaction (2.2). The water undergoes these two stages (nitrification and denitrification) multiple times via recirculation of the water. Finally, recall that for the nitrification oxygen is required, and the largest amount of oxygen comes from the aerators. The human supervisor that controls the aerators, has thus direct influence on the amount of ammonium that is broken down into nitrate.

Another zone in the activated sludge tank is the anaerobic zone. In this region neither oxygen nor nitrate is present. Here, the phosphor removal takes place. This is either done by bacteria (phosphate uptake) or done by using chemical phosphate removal. In the latter case, a metal ion (often iron) is used and one has

$$Fe^{3+} + H_3PO_4 \rightarrow FePO_4 + 3H^+. \tag{2.4}$$

Iron(III) phosphate, $FePO_4$, can then be captured and removed from the water.

After the biological treatment, the activated sludge needs to be removed from the water. The water enters a second settler, in which the activated sludge will sink to the bottom of the tank due to gravity, such that only the treated water is left. A part of the sludge is being reused in the biological treatment tank, to preserve a population of bacteria. Otherwise all active bacteria would flush out of the treatment plant. The effluent will flow to rivers, lakes, oceans or wetlands.

Chapter 3

Activated Sludge Models

In this chapter, the Activated Sludge Model 1 (ASM1) will be discussed. It is a mathematical model describing the biological reactions that take place inside the activated sludge tank. The physical basis of this model are mass-balance equations. In 1986, the ASM1 was presented by the IAWQ (International Association on Water Quality, formerly known as the IAWPRC, International Association on Water Pollution Research and Control). The ASM1 model allows for dynamic simulation of organic matter degradation and of the nitrification and denitrification processes.

Over the years, a couple of updated or extended activated sludge models became available. In 1995, ASM2 was presented. This model also takes into account the biological phosphorus removal [4]. An updated version was presented in 1999 known as ASM2d, which also includes denitrifying phosphorus-accumulation organisms. In 1999 ASM3 was presented, which is an extended version of ASM1, where some additional concepts of the acitvated sludge processes were included. This include the kinetic expressions of nitrogen and the storage of poly-hydroxy-alkanoates. Since ASM1 is the most elementary model and the foundation for ASM2, ASM2d and ASM3, we will now study the ASM1 in greater detail.

The ASM1 model involves 8 processes, incorporating 13 components [5]. Processes include the growth and decay of biomass (either heterotrophic or autotrophic) and hydrolysis. The 13 components of the model, or states, consists of soluble components S and particulate components X. These 13 wastewater characteristics are X_i, X_S, $X_{B,H}$, $X_{B,A}$, X_D, S_i, S_S, S_O, S_{NO}, S_{NH}, S_{NS}, X_{NS} and S_{ALK}. The description of these components is given in Table 3.1. In Figure 3.1 the relations between these components is illustrated. This figure is taken from [6].

State	Description	Unit
S_I	soluble inert organic matter	M(COD)L^{-3}
S_S	readily biodegradable substrate	M(COD)L^{-3}
X_I	particulate inert organic matter	M(COD)L^{-3}
X_S	slowly biodegradable substrate	M(COD)L^{-3}
$X_{B,H}$	active heterotrophic biomass	M(COD)L^{-3}
$X_{B,A}$	active autotrophic biomass	M(COD)L^{-3}
X_P	particulate products arising from biomass decay	M(COD)L^{-3}
S_O	oxygen	M(-COD)L^{-3}
S_{NO}	nitrate and nitrite nitrogen	M(N)L^{-3}
S_{NH}	$NH_4^+ + NH_3$ nitrogen	M(N)L^{-3}
S_{ND}	soluble biodegradable organic nitrogen	M(N)L^{-3}
X_{ND}	particulate biodegradable organic nitrogen	M(N)L^{-3}
S_{ALK}	alkalinity	molar

Table 3.1: Overview of the states (components) in the Activated Sludge Model 1.

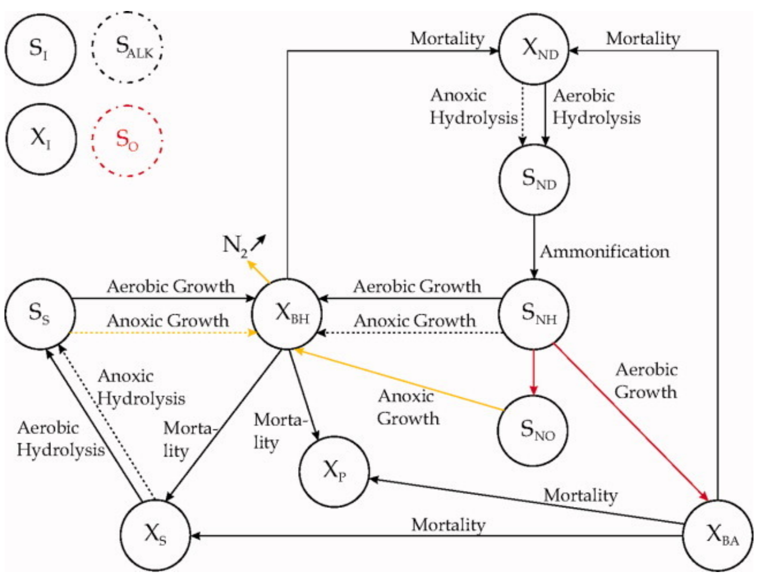


Figure 3.1: Interaction between the components in the ASM1. The figure is taken from [6].

In Figure 3.1, S_I and X_I denote the soluble and particulate inert organic matter, respectively, so they do not interact with the other components. For clarity, the connections of S_O and S_{ALK} to the other components are not drawn, as they play a role in most reactions.

To write down mathematically how these components change over time, it is a good idea to look at the *Monod equation.* This equation is an important physical model that describes the growth of a microorganism [4]. Let μ denote the specific growth rate of a particular microorganism, and let S denote the concentration of the substrate used for growth. The Monod equation is

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

where $\mu_{\max}$ is the maximum specific growth rate of the microorganism, and K_S is the half-velocity constant, i.e., the value of S for which $\frac{\mu}{\mu_{\max}} = 0.5$.

Another widely used expression in the mathematical description of the ASM1, are so-called switching functions. These functions are used in the process rate equations and can turn either on or off, depending on the environmental conditions. As an example, consider the following switching function:

$$\frac{S_O}{K_O + S_O},$$

where S_O is the amount of dissolved oxygen and K_O is a constant for the maximal growth rate. Let us now consider the bacteria for nitrification. In the previous chapter, we have already seen that these bacteria need oxygen. So, under aerobic conditions, this component will grow. If, however, the concentration of dissolved oxygen tends to zero, the biomass will stop growing. We see that the above switching function is 1 as K_O approaches 0, while the switching function goes to 0 if S_O is 0. In the latter case, the switching function

$$\frac{K_O}{S_O + K_O},$$

approaches 1 if there is no dissolved oxygen present, and it approaches 0 as K_O goes to zero.

Recall that ASM1 contains 13 components (states) and models 8 processes. Each process has a specific process rate, which is denoted by v_i. A description of all 8 processes together with their process rates is given in Table 3.3.

We are now in a position to present the complete Activated Sludge Model 1. This is done in Table 3.2 and Table 3.3. The model is described using the matrix notation. Each row corresponds to one specific process, while each column denotes a particular component. We will now explain how to read Table 3.2.

S_I	S_S	X_I	X_S	$X_{B,H}$	$X_{B,A}$	X_P	S_O	S_{NO}	S_{NH}	S_{ND}	X_{ND}	S_{ALK}	
	$\frac{-1}{Y_H}$			1			$\frac{-1+Y_H}{Y_H}$		$-i_{XB}$			$\frac{-i_{XB}}{14}$	v_1
	$\frac{-1}{Y_H}$			1				$\frac{-1+Y_H}{2.86Y_H}$	$-i_{XB}$			$\frac{1-Y_H}{14 \cdot 2.86Y_H} - \frac{i_{XB}}{14}$	v_2
					1		$\frac{-4.57+Y_A}{Y_A}$	$\frac{1}{Y_A}$	$-i_{XB} - \frac{1}{Y_A}$			$-\frac{i_{XB}}{14} - \frac{1}{7Y_A}$	v_3
			$1-f_p$	-1		f_p					$i_{XB} - f_p i_{XP}$		v_4
			$1-f_p$		-1	f_p					$i_{XB} - f_p i_{XP}$		v_5
									1	-1		$\frac{1}{14}$	v_6
	1		-1										v_7
										1	-1		v_8

Table 3.2: The Activated Sludge Model 1 in matrix notation.

	Process	Process rate
v_1	aerobic growth of heterotrophs	$\hat{\mu}_H \cdot \frac{S_S}{K_S+S_S} \cdot \frac{S_O}{K_{O,H}+S_O} \cdot X_{B,H}$
v_2	anoxic growth of heterotrophs	$\hat{\mu}_H \frac{S_S}{K_S+S_S} \cdot \frac{K_{O,H}}{K_{O,H}+S_O} \cdot \frac{S_{NO}}{K_{NO}+S_{NO}} \cdot \eta_g \cdot X_{B,H}$
v_3	aerobic growth of autotrophs	$\hat{\mu}_A \cdot \frac{S_{NH}}{K_{NH}+S_{NH}} \cdot \frac{S_O}{K_{O,A}+S_O} \cdot X_{B,A}$
v_4	decay of heterotrophs	$b_H X_{B,H}$
v_5	decay of heterotrophs	$b_A X_{B,A}$
v_6	ammonification of soluble organic nitrogen	$k_a S_{ND} X_{B,H}$
v_7	hydrolysis of entrapped organics	$k_h \cdot \frac{X_S/X_{B,H}}{K_X+X_S/X_{B,H}} \cdot \left(\frac{S_O}{K_{O,H}+S_O} + \eta_h \cdot \frac{K_{O,H}}{K_{O,H}+S_O} \cdot \frac{S_{NO}}{K_{NO}+S_{NO}}\right) \cdot X_{B,H}$
v_8	hydrolysis of entrapped organic nitrogen	$v_7 \cdot \frac{X_{ND}}{X_S}$

Table 3.3: Process rates of the ASM1.

To describe mathematically the change of each component over time, we have to look at Table 3.2. Let x_j denote component j, then we have

$$\frac{dx_j}{dt} = \sum_{i=1}^{8} a_{i,j} v_i, \quad 1 \le j \le 13,$$

where v_i denotes the process rates (from Table 3.3) and $a_{i,j}$ denotes the stoichiometric coefficient. If a cell in the matrix is empty, it means that the stoichiometric coefficient is 0.

As an example, consider now the behavior of dissolved oxygen, S_O, this is the 8$^{\text{th}}$ component so we look at column 8 in Table 3.2. We see that S_O depends on the aerobic growth of heterotrophic bacteria and on the growth of autotrophic bacteria. The stoichiometric coefficients are denoted in Table 3.2 and the process rates in Table 3.3. We have

$$\begin{aligned}\frac{dS_O}{dt} =& -\frac{1-Y_H}{Y_H} \cdot \hat{\mu}_H \cdot \frac{S_S}{K_S+S_S} \cdot \frac{S_O}{K_{O,H}+S_O} \cdot X_{B,H} \\ & - \frac{4.57-Y_A}{Y_A} \cdot \hat{\mu}_A \cdot \frac{S_{NH}}{K_{NH}+S_{NH}} \cdot \frac{S_O}{K_{O,H}+S_O} \cdot X_{B,A}\end{aligned}$$

As another example, consider the differential equation for ammonia and ammonium, S_{NH}. In the aerobic zone both the heterotrophic and autotrophic bacteria grow, and in the anoxic zone there is also growth of the heterotrophs. Finally also the ammonification of soluble organic nitrogen needs to be taken into account. We see that

$$\begin{aligned}\frac{dS_{NH}}{dt} =& - i_{XB} \cdot \hat{\mu}_H \cdot \frac{S_S}{K_S+S_S} \cdot \frac{S_O}{K_{O,H}+S_O} \cdot X_{B,H} \\ & - i_{XB} \cdot \hat{\mu}_H \cdot \frac{S_S}{K_S+S_S} \cdot \frac{K_{O,H}}{K_{O,H}+S_O} \cdot \frac{S_{NO}}{K_{NO}+S_{NO}} \cdot \eta_g \cdot X_{B,H} \\ & - \left(i_{XB} + \frac{1}{Y_A}\right) \cdot \hat{\mu}_A \cdot \frac{S_{NH}}{K_{NH}+S_{NH}} \cdot \frac{S_O}{K_{O,A}+S_O} \cdot X_{B,A} \\ & + k_a \cdot S_{ND} \cdot X_{B,H},\end{aligned}$$

which can be simplified to

$$\begin{aligned}\frac{dS_{NH}}{dt} =& -\frac{S_S}{K_S+S_S} \cdot \left\{ \frac{S_O}{K_{O,H}+S_O} + \frac{K_{O,H}}{K_{O,H}+S_O} \cdot \frac{S_{NO}}{K_{NO}+S_{NO}} \cdot \eta_g \right\} \cdot i_{XB} \cdot \hat{\mu}_H \cdot X_{B,H} \\ & - \left(i_{XB} + \frac{1}{Y_A}\right) \cdot \hat{\mu}_A \cdot \frac{S_{NH}}{K_{NH}+S_{NH}} \cdot \frac{S_O}{K_{O,A}+S_O} \cdot X_{B,A} \\ & + k_a \cdot S_{ND} \cdot X_{B,H}.\end{aligned}$$

Finally, there are also 19 fixed values appearing in the model equations of Table 3.2. These are Y_H, Y_A, f_p, i_{XB}, i_{XP}, μ_H, b_H, K_S, K_{OH}, K_{NO}, μ_A, b_A, $K_{O,A}$, K_{NH}, η_g, k_a, K_h, K_X and η_h. In Table 7.1 in Appendix A, a brief description of these constants is given.

We studied the Activated Sludge Model 1 to get a better understanding of the kinematics and reactions that take place in an activated sludge tank. However, the model is not very useful yet. Up to now, the described differential equations describe the behavior of the components in a closed vessel. It is as if one has a sealed off tank containing a particular amount of water and activated sludge, and then the equations from Table 3.2 describe the behavior of the components in this tank in the long run. The differential equations do not take into account additional inputs or outputs to and from the tank.

As such, the described Activated Sludge Model 1 is not very useful for our study, because we are dealing with extra inputs and outputs. We have inflow of wastewater and outflow of wastewater, we have additional oxygen that can be supplied to the tank by the aerators and finally we have a part of the activated sludge that is being reused. All these factors play an important role and must be incorporated in the differential equations.

Unfortunately, we were not sure how to implement these inputs and outputs to the model. One obstacle was that one needs specific weighting factors, or constants. For example, the amount of oxygen that is supplied through the aerators is measured in units of milligrams per liter (mg/L), however, this quantity needs to be translated to a (negative) Chemical Oxygen Demand (-COD), and we did not know how to do that. On top of that, a part of the activated sludge is being reused, but we do not know its composition. One has to make certain assumptions on the percentage of heterotrophic and autotrophic bacteria in the activated sludge, and we do not have reasonable guesses for that. This is why we decided to not delve further into the research of the Activated Sludge Models, and instead we focused on another physics based model that describes the relationship between oxygen and total nitrogen.

Chapter 4

Design of the advanced WOMBAT® controller

In this chapter an overview of the functional design of the advanced WOMBAT® will be presented. As stated in the introduction, the WOMBAT® and advanced WOMBAT® are installed on the wastewater treatment plant Westpoort (Amsterdam) and they work properly. Before explaining the mechanism of the advanced WOMBAT® controller, we will first study the physical model that forms the basis of the advanced WOMBAT® controller.

This physical model tells us the relationship between (dissolved) oxygen and the total ammonium in the activated sludge tank. This relationship is depicted in Figure 4.1, taken from [7].

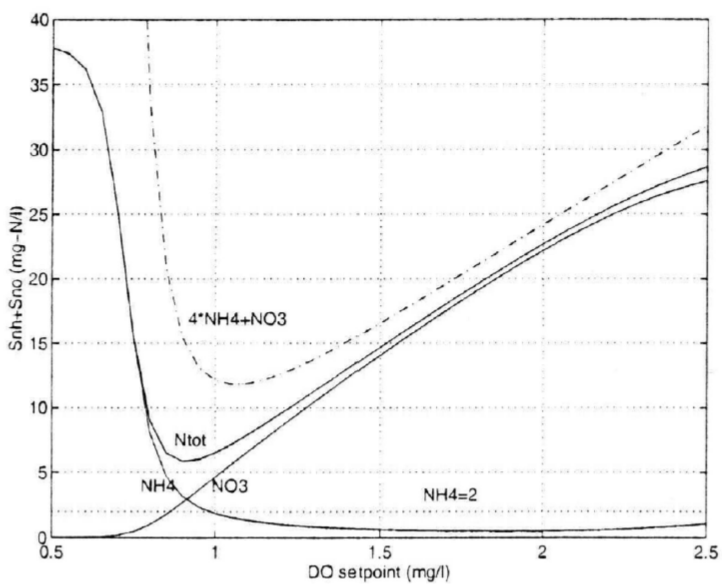


Figure 4.1: Ammonium, nitrate and total nitrogen as a function of dissolved oxygen, at a temperature of $T = 12.0°C$. The figure is taken from [7].

The figure illustrates the relationship between the concentration of ammonium and nitrate, as function of the concentration of oxygen. Also the total nitrogen concentration is illustrated, which is simply the sum of the ammonium and nitrate levels. As can be seen from the picture, the relationship between oxygen and ammonium is roughly speaking inversely proportional. This makes sense physically. We see that the ammonium level is very high when there is almost no dissolved oxygen in the water, because the aerobic bacteria cannot perform their task then. This is why the aerators at Westpoort are controlled in such a way that the dissolved oxygen is at least 0.5 mg/L. As more and more oxygen is supplied to the tank, more nitrification reactions take place, and the ammonium is broken down. We see that the level of nitrate is roughly proportional to the level of oxygen.

It should be noted that the curves in the above figure are also depending on the flow and temperature of the water. In the figure below, taken from [8], a second situation is depicted, at a different temperature. We see that at a lower temperature, more oxygen is required before nitrification can take place. The total nitrogen is also significantly higher compared to the situation at higher temperature. This is because bacteria are more active at higher temperatures, so they perform better.

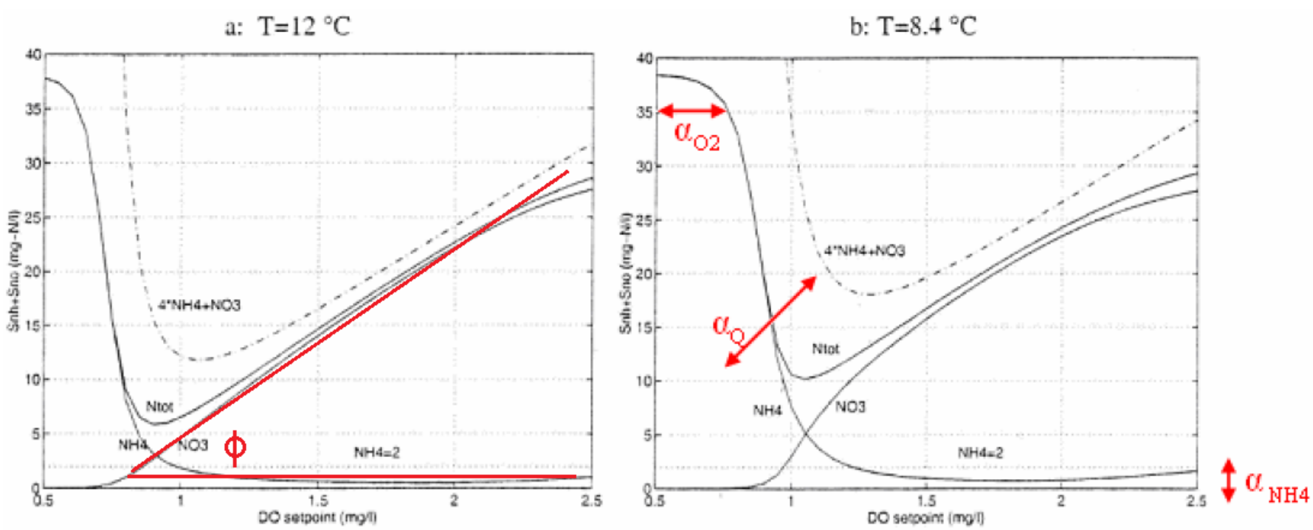


Figure 4.2: The nitrogen concentrations at two different temperatures. The figure is taken from [8].

Based on the above figure, a formula for the ammonium concentration as function of the oxygen setpoint is given by the following expression, taken from [8]:

$$NH_4^m(t) = \frac{\alpha_Q \cdot Q(t)}{O_2(t) - \alpha_{O_2}} \cdot \frac{T_{\text{ref}} - T_{\min}}{T(t) - T_{\min}} + \Big(\alpha_{NH_4} + \alpha_T(t) \cdot (T_{\max} - T(t))\Big), \tag{4.1}$$

The superscript m in the ammonium concentration NH_4^m stands for 'model', since it is the ammonium concentration according to this physical model.

We see that NH_4^m is inversely proportional to the oxygen level, O_2, and proportional to the flow, Q. The α's represent parameters that can be adjusted, such that no matter what the flow, oxygen or temperature is, the above formula will always give a good prediction of the ammonium level.

Here, α_Q depends on the dirt concentration in the wastewater. If there is a large amount of dry weather flow, α_Q has a different value than in the case for which there is a lot of wet weather flow in the influent. The parameter α_{O_2} basically represents the minimal amount of oxygen that needs to be supplied such that ammonium will be broken down into nitrate. The parameter α_{NH_4} is the asymptotic concentration of ammonium, i.e., the level of ammonium when we aerate maximally. In that case, since there is enough oxygen to transform all ammonium into nitrate, the ammonium concentration tends to zero and α_{NH_4} is thus negligible. Finally, α_T is the base concentration of ammonium relative to the temperature. From recorded data it followed that α_T is very small, and the term $\alpha_T(t)\cdot(T_{\max}-T(t))$ in expression (4.1) is negligible as well. Finally, $T_{\text{ref}}, T_{\min}$ and $T_{\max}$ denote the reference, minimal and maximal temperature of the wastewater in the activated sludge tank, respectively. The temperature of the water changes very slowly, so the factor $\frac{T_{\text{ref}}-T_{\min}}{T(t)-T_{\min}}$ changes very slowly as well. It can therefore be ignored, since the parameter α_Q can always be updated fast enough to incorporate big changes in temperature.

In this physical model it is assumed that the level of nitrate is proportional to the level of oxygen. We let ϕ denote the ratio between the ammonium concentration and the nitrate concentration. If we aerate at least an amount of α_{O_2}, this angle ϕ is constant (see Figure 4.2). We then have

$$NO_3^m(t) = \tan(\phi)\cdot O_2(t).$$

The total amount of nitrogen in the activated sludge tank is now

$$N_{\text{tot}}^m(t) = NH_4^m(t) + NO_3^m(t).$$

These formulas for the ammonium, nitrate and total nitrogen concentration form the basis of the advanced WOMBAT® controller. Since the control goal is to aerate optimally, by which we mean that the amount of total nitrogen is the lowest, the optimal oxygen setpoint can be computed by solving

$$\frac{\partial N_{tot}^m}{\partial O_2} = 0.$$

So we get:

$$\begin{aligned}\frac{\partial}{\partial O_2}\left(\frac{\alpha_Q\cdot Q(t)}{O_2(t)-\alpha_{O_2}}\cdot\frac{T_{\text{ref}}-T_{\min}}{T(t)-T_{\min}} + \Big(\alpha_{NH_4}+\alpha_T(t)\cdot(T_{\max}-T(t))\Big) + \tan(\phi)\cdot O_2(t)\right) &= 0\\ -\frac{\alpha_Q\cdot Q(t)}{(O_2(t)-\alpha_{O_2})^2}\cdot\frac{T_{\text{ref}}-T_{\min}}{T(t)-T_{\min}} + \tan(\phi) &= 0\end{aligned}$$

This equation can be solved explicitly for $O_2(t)$, and one finds that the minimum of total nitrogen is achieved at the following oxygen setpoint, [8]:

$$O_2^{\text{set}}(t) = \alpha_{O_2} + \sqrt{\frac{\alpha_Q \cdot Q(t)}{\tan(\phi)} \cdot \frac{T_{\text{ref}} - T_{\min}}{T(t) - T_{\min}}}. \tag{4.2}$$

It is thus desirable that the aerators steer towards this oxygen setpoint, because at this oxygen level the effluent quality is maximal.

Now, in the advanced WOMBAT® controller, the parameters are updated automatically by input measurements from the wastewater treatment plant. Because of the automated updating, formulas (4.1) and (4.2) can be simplified a little bit. The underlying physical model of the advanced WOMBAT® controller consists now of the following two formulas:

$$NH_4 = \frac{\alpha_1 Q}{O_2 - \alpha_2}, \tag{4.3}$$

$$O_{2,\text{set}} = \alpha_2 + \sqrt{\alpha_1 \cdot \alpha_3 \cdot Q}. \tag{4.4}$$

Formulas (4.3) and (4.4) have the same form and characteristics as formulas (4.1) and (4.2). The parameters α_1, α_2 and α_3 are updated repeatedly, such that the above expressions always provide an accurate description of the physical model. The physical interpretation of these parameters are as follows. The parameter α_1 represents the dirt load of the influent, or the breakdown speed of ammonium. Parameter α_2 is the minimal oxygen concentration that needs to be supplied in order to start the breakdown of ammonium into nitrate. Finally, α_3 is a factor that can be set by the human operator and it represents the proportion of ammonium versus nitrate in the effluent.

We will now explain the design of the advanced WOMBAT® controller in more detail. A complete overview of the functional design of the advanced WOMBAT® can be found in Appendix B, taken from [3]. In short, the advanced WOMBAT® continuously steers towards the optimal oxygen setpoint.

First of all, the advanced WOMBAT® controller makes use of filtered input signals. At the wastewater treatment plant in Westpoort the following components are measured (among others): oxygen concentration O_2, ammonium concentration NH_4, inflow Q and temperature of the water T. Usually the measurements take place every minute, so the values will be averaged using a moving average filter. For example, if the filter length of the ammonium filter, L_N, is half an hour (30 minutes), the ammonium concentration at time instance t_k is in fact the average over all ammonium concentrations at time instances $t_{k-1}, t_{k-2}, \ldots, t_{k-30}$.

It should be noted that different variables have different filter lengths. For example, the filter length of ammonium, L_N, is on default 30 minutes, but the length of the oxygen filter and temperature filter, L_{O_2} and L_T, are set to be 60 minutes. The lenght of the flow filter is usually 180 minutes. Also note that in the prediction and evaluation steps different measurements of oxygen and flow are used. In the prediction zone we make use of a delayed measurement of the flow, denoted by D_Q.

The advanced WOMBAT® controller uses these filtered input signals to predict the ammonium concentration and based on that the optimal oxygen setpoint. The predicted ammonium level can be compared with the actual ammonium measurement, and this error gives an indication how well the prediction is. The α-parameters appearing in the model equations are also updated regularly. This evaluation/update/prediction cycle is run continuously. The advanced WOMBAT® thus continuously searches for the optimal oxygen setpoint, i.e., the setpoint where the total amount of nitrogen is the lowest, and steers towards this oxygen setpoint.

It should be noted that in this cycle also a delay time Δt is implemented. This is done because it takes a while for the water to flow through the wastewater treatment plant. Suppose the water enters the treatment plant and the measurements indicate that there should be aerated intensively, because this batch has a high dirt load. Then one does not want to aerate directly, since the polluted water needs to get to the aerobic zone first, which normally takes one to two hours.

Finally, not always the calculated oxygen setpoint O_2^c is used as the new setpoint. The computed setpoint should be between a minimum and maximum value, in general this is between 0.5 mg/L and 5.0 mg/L. This is because there is no point in aerating less than 0.5 mg/L since heterotrophic bacteria will die then. The aerators will also not be aerating more than 5.0 mg/L since that would be a waste of energy already. Also, if there is a large inflow of wet weather flow (rainwater), often a wet weather flow conditional setpoint is used. On default this is a value between 3.0 mg/L and 3.5 mg/L.

Chapter 5

Data analysis in Matlab

As stated the advanced WOMBAT® continuously steers towards the optimal oxygen setpoint, $O_{2,\text{set}}^{\text{opt}}$. By that we mean that it is the oxygen concentration where the effluent quality is maximal, since the total nitrogen concentration is minimal. In Figure 5.1 this setpoint is again depicted.

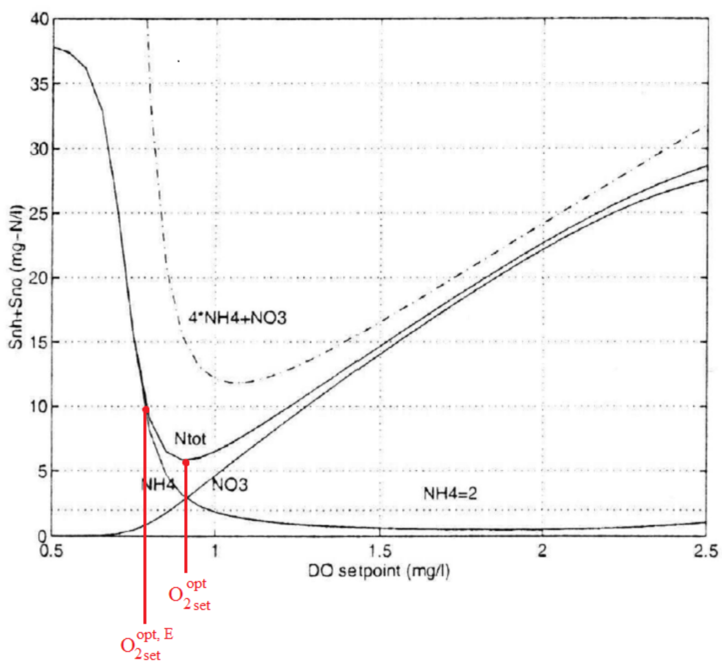


Figure 5.1: The curves of ammonium, nitrate and total nitrogen as function of the concentration of oxygen, together with the optimal oxygen setpoint $O_{2,\text{set}}^{\text{opt}}$ and the optimal energy oxygen setpoint $O_{2,\text{set}}^{\text{opt, E}}$.

An interesting question is whether we can reduce the aeration costs, by steering towards a lower oxygen setpoint. At this lower oxygen setpoint still enough ammonium should be broken down into nitrate, such that the Water Framework Directive requirements are still fulfilled. In other words, we choose to aerate a little less, meaning that a smaller concentration of ammonium is broken down into nitrate, however the concentration of ammonium is still within the legal bounds (the ammonium level should be below 2 mg/L, and the total nitrogen should be below 10 mg/L). The optimal oxygen setpoint and our proposed new oxygen setpoint are depicted in Figure 5.1. The new setpoint is denoted by $O_{2,\text{set}}^{\text{opt, E}}$, where the superscript 'opt, E' stands for optimal Energy consumed. Sometimes this optimal energy oxygen setpoint $O_{2,\text{set}}^{\text{opt, E}}$ is also called the minimal oxygen setpoint, since it is the oxygen setpoint where the amount of energy consumed is minimal under the Water Framework Directive constraints.

The objective now is to find a formula for this new oxygen setpoint $O_{2,\text{set}}^{\text{opt, E}}$. As stated in Chapter 4, the formula for the optimal oxygen setpoint is based on the minimal value of the total nitrogen function. The problem here is that the function describing the total nitrogen was based on an educated guess that the relationship between ammonium and oxygen is inversely proportional. This turned out to be a good guess and by adjustment of the α-parameters, we can always shift the curve such that it fits the theoretical relationship very well.

We now want to study if this inversely proportional relationship between the ammonium and oxygen concentration is also present in real life data. If it is, we can perform a data analysis and use a curve fitting tool in Matlab to find a precise expression for this curve. This formula is then not depending on the α-parameters anymore, and we can use this exact formula to compute the minimal oxygen setpoint by finding the value of oxygen where the amount of ammonium is precisely 2 mg/L.

First of all, we did a literature research and found the following result by Floris Beltman, who did an internship at Witteveen+Bos in 2008 [9]. He performed a simulation of the wastewater treatment plant of Amsterdam Westpoort in the software package Simba. He plotted the ammonium levels and oxygen levels and the result is given in Figure 5.2.

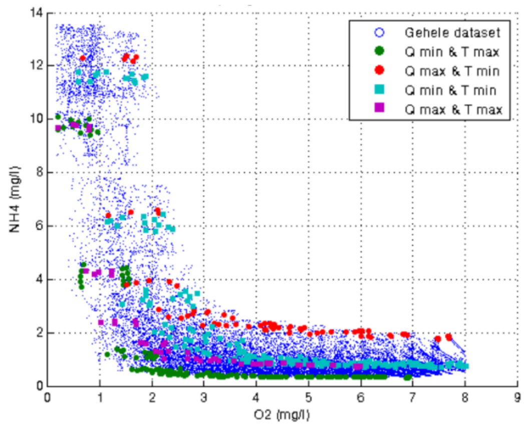


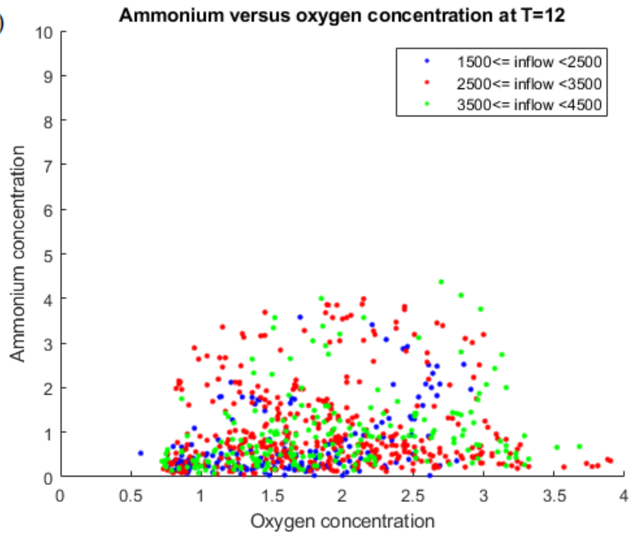
Figure 5.2: Simulation results of the wastewater treatment plant of Amsterdam Westpoort. This simulation was carried out in [9].

We see that in the simulations the inverse proportional relationship between ammonium and oxygen is clearly present. We also note that this curve depends on the temperature and flow of the wastewater, as is also explained in Chapter 4.

The above simulation results give us hope for the real life situation. We now studied an actual dataset of measurements from the Amsterdam Westpoort wastewater treatment facility. Measured values include the concentration of ammonium, dry matter, phosphate, nitrate and oxygen, the temperature of the water and also the influent flow and effluent flow of the wastewater. In fact, often nitrate is measured twice, since it is measured in the anoxic zone and in the aerobic zone. In this way, it can be computed how much nitrate is broken down.

The first dataset we considered contains measurements from January 2009 to June 2010. We ran a data analysis on this dataset and in Figure 5.3a the first results are presented. We sorted all the data according to the influent flow and to the temperature. One would then expect that the sorted datapoints are located on a curve as predicted by the theory. Unfortunately, we do not observe the inversely proportional relationship between ammonium and oxygen. One reason for that is the following. We note that most of the ammonium values are very low, less than 2.0 mg/L. This suggest that the datapoints belong to the 'tail' of the ammonium-curve. The high peak corresponding to low oxygen concentrations is not present, because there is already enough oxygen in the tank, so we do not have any datapoints corresponding to those low oxygen values. Also note that the minimal oxygen level is 0.5 mg/L, because this is the minimal value of the aerators.

(a)



(b)

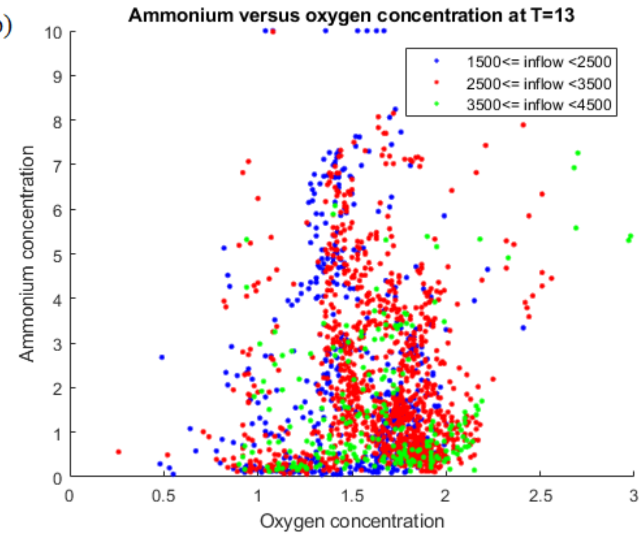


Figure 5.3: Real life measurements of the ammonium and oxygen concentration at different temperatures. This figure contains data from January 2010 to June 2010.

In Figure 5.3b a second plot is given, for a different temperature. Also here the relationship between the ammonium and oxygen concentration is not present.

Then, we looked at a different dataset that consists of recorded measurements from January 2014 to June 2014. The reason for that is that back in 2009 the control law used at Amsterdam Westpoort was still the decision matrix. In 2014, the advanced WOMBAT® was in use and this might unfluence the oxygen-ammonium pairs. In Figure 5.4a the situation is shown at a temperature of 22°C. Again, we plotted the datapoints in different colors for different amounts of inflow. The results are slightly better, but there is a large vertical line around the oxygen level of 0.5 mg/L. This is probably because one of the sensors was broken, so that the ammonium value could not be measured. The ammonium sensor only works in the range of 0.0 to 10.0 mg/L, and we suspect that if the value cannot be measured it gives as output the entire range of values.

Finally, in Figure 5.4b the situation for a different temperature is depicted. We see again that the theoretical relantionship between ammonium and oxygen cannot be observed from the data, unfortunately.

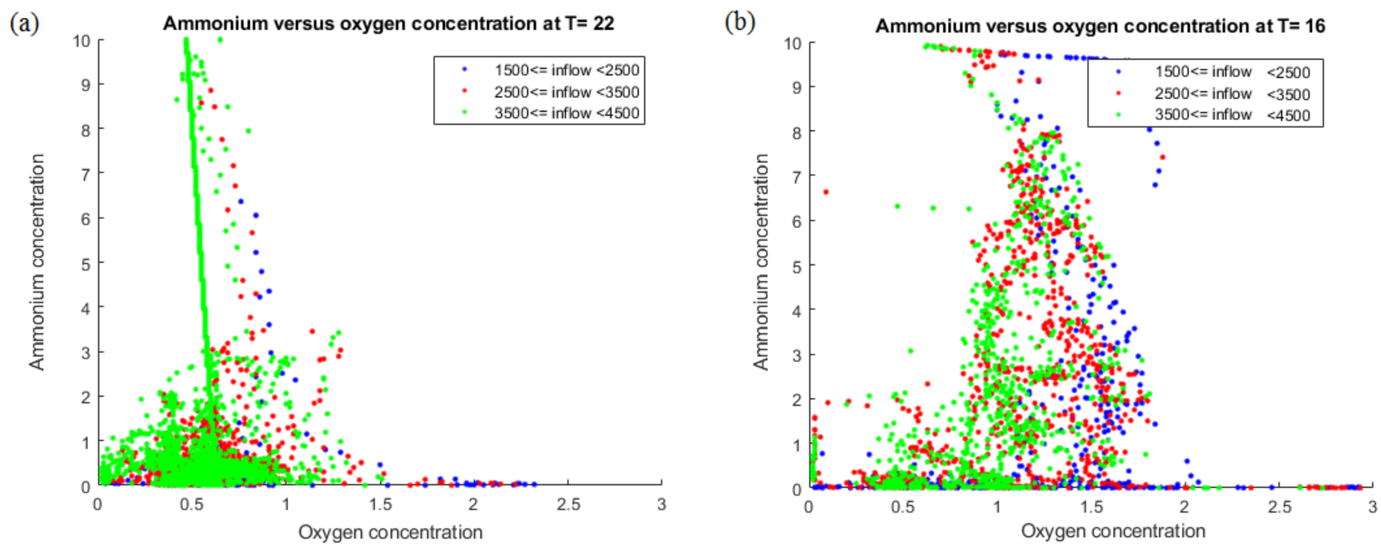


Figure 5.4: Real life measurements of the ammonium and oxygen concentration at different temperatures. This figure contains data January 2014 to June 2014.

To conclude, we looked at two different datasets and we sorted the data based on temperature and influent flow. The expected curve between ammonium and oxygen measurements cannot be detected in the graphs. The simulation showed promising results, but the reality was unfavorable. This is because in reality the controller always steers towards oxygen setpoints within a given range, often between 0.5 and 2.5 mg/L. Excessive situations where the oxygen concentration is very low or very high are not often occuring in real life, because the aim of the controller is precisely that such cases do not occur. It is therefore difficult to conclude whether the inversely proportional relationship is present, because we have only datapoints for a small range of oxygen concentrations. In simulations, of course, one can simulate these exceptional cases where the oxygen concentration is out of bounds. Put differently, in a simulation, one deals with an open-loop system, and one can change the input variables as desired. In reality, the system is closed-loop, so this is not possible.

Since the inversely proportional relationship between oxygen and ammonium is not present in the real life data, there is no point in using a curve fitting tool to find the best fitted expression for the curve. We therefore stick to the simplified ammonium equation proposed in the functional design of the advanced WOMBAT® controller.

Chapter 6

Less energy consuming oxygen setpoints

In the previous chapter we did not find an accurate expression for the ammonium concentration as a function of the oxygen level, unfortunately. We hoped that if such formula exists, we could use that to find the optimal energy oxygen setpoint. Recall that the optimal energy oxygen setpoint is something different than the optimal energy setpoint. The optimal setpoint is the oxygen level where a maximal amount of ammonium is broken down into nitrate, and the total nitrogen is minimal. By optimal energy oxygen setpoint we mean that this is the concentration where the ammonium levels are just below 2 mg/L, and the total nitrogen in the activated sludge tank is still less than 10 mg/L. In this way, the conditions of the Water Framework Directive are still satisfied, but we have aerated less. This optimal energy oxygen setpoint, sometimes called the minimal oxygen setpoint, is thus consuming less energy compared to the optimal oxygen setpoint. This is beneficial for the total costs of the wastewater treatment plant.

As said, the precise minimal oxygen setpoint is yet unknown, but we do know that we can at least use a lower oxygen setpoint than the optimal oxygen setpoint. From Figure 4.1 it is clear that within a small neighborhood of the optimal oxygen setpoint, the ammonium levels are still within the legal marges.

We therefore propose the following adjustment to the advanced WOMBAT® controller. Instead of steering towards the optimal oxygen setpoint, we steer now to a fraction of this setpoint. Mathematically speaking, we have the following formula for our proposed optimal energy oxygen setpoint

$$O_{2,\text{set}}^{\text{opt, E}} = \min(\max(p \cdot O_{2,\text{set}}^{\text{opt}}, O_{2,\text{set}}^{\min}), O_{2,\text{set}}^{\max}), \qquad p \in [0,1],$$

where p is a factor between 0 and 1. For example, if $p = 0.90$, this means that we set the new oxygen setpoint 10% lower than the optimal oxygen setpoint, such that we have to aerate less, and consequently, save energy (hence, money). By $O_{2,\text{set}}^{\min}$ and $O_{2,\text{set}}^{\max}$ we denote the minimum and maximum oxygen setpoint, these values are set by the wastewater treatment plant.

Based on this new minimal oxygen setpoint, we also calculated the predicted ammonium level, by using the corresponding formula from the advanced WOMBAT® controller:

$$NH_4^{\text{pre}} = \frac{\alpha_1 \cdot Q^{\text{f}}}{O_{2,\text{set}}^{\text{opt, E}} - \alpha_2}.$$

We have run calculations in Excel to test the above idea. In 2017, intern Phung Le Duc has simulated the advanced WOMBAT® controller in Excel, using the programming language Visual Basic for Applications (VBA), [10]. It should be remarked that the program code works slightly different than the functional design, described in Chapter 4. In the functional design, the prediction/update/evaluation cycle is one loop. When this cycle was modelled in VBA, this loop had to be broken down into five loops. The reason for that are the different lengths of the filters. Since the length of the moving average filters are different, this poses problems for the execution order of the program. For example, in the evaluation phase one might need an input measurements that has not been computed yet. That is why Phung Le Duc has computed all the average measured (i.e., filtered) values first. His solution does not contradict the functional design, and the program still yields the proper results.

We have adjusted his program so that it now includes our proposed minimal oxygen setpoint, and its corresponding ammonium concentration prediction. We have run the program multiple times for different values of p. Finally, the ammonium levels corresponding to the oxygen predictions can be plotted in a figure. In Figure 6.1, this is done for the case where $p = 0.90$. For clarity we have also drawn the maximal ammonium concentration of 2.0 mg/L in black. Also the mean and median of the ammonium concentration are plotted in the figure. Recall that the median can be thought of as the 'middle' value, since it seperates the lower half from the higher half. The reason why we computed the median as well, is because the mean can give a distorted view of reality. It can happen that the set of ammonium values has a relative high mean because there are a couple of outliers, while most of the ammonium concentrations are low. That is why the median can help us to give insight as well.

In the case of $p = 0.90$, we found that the average is 2.1820 mg/L and the median is 1.9808 mg/L. That means the ammonium value of the wastewater will be too high on average in reality, while in at least 50% the ammonium level is still below 2.0 mg/L. This situation is not favorable in reality, so we conclude that we cannot reduce the amount of aeration by 10%.

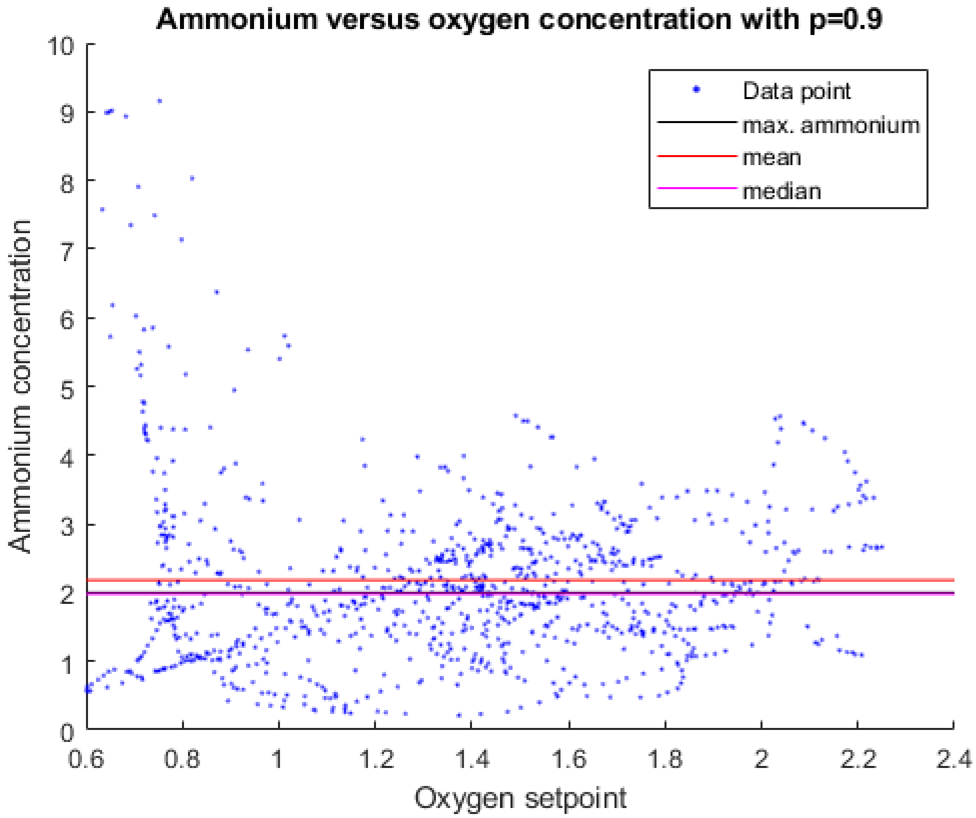


Figure 6.1: The optimal energy oxygen setpoints together with the ammonium levels, with $p = 0.90$.

The situation with $p = 0.95$ is depicted in Figure 6.2. This means that the newly computed oxygen setpoint is 5% lower than the optimal oxygen setpoint. We computed that the average ammonium concentration will be 1.9806 mg/L, and the median is 1.8368 mg/L. Both values are below 2.0 mg/L, so we propose to aerate 5% less in order to save energy. Note that roughly 60% of the energy consumption stems from the aeration process. If we can bring this percentage down, a lot of energy and hence money can be saved. Assume the controller can incorporate these changes and works properly. This boils down to a saving of approximately €3200 per year [11]. If the above adjustment is made to the advanced WOMBAT® controller, this will cost approxiamtely €1000 in terms of labor costs. The payback period is thus less than 4 months [11]. This is very short, because in general a wastewater treatment plant will only incorporate adjustments to their facility that have a payback period of at most 5 to 10 years. Having a payback period of only 4 months is thus very favorable.

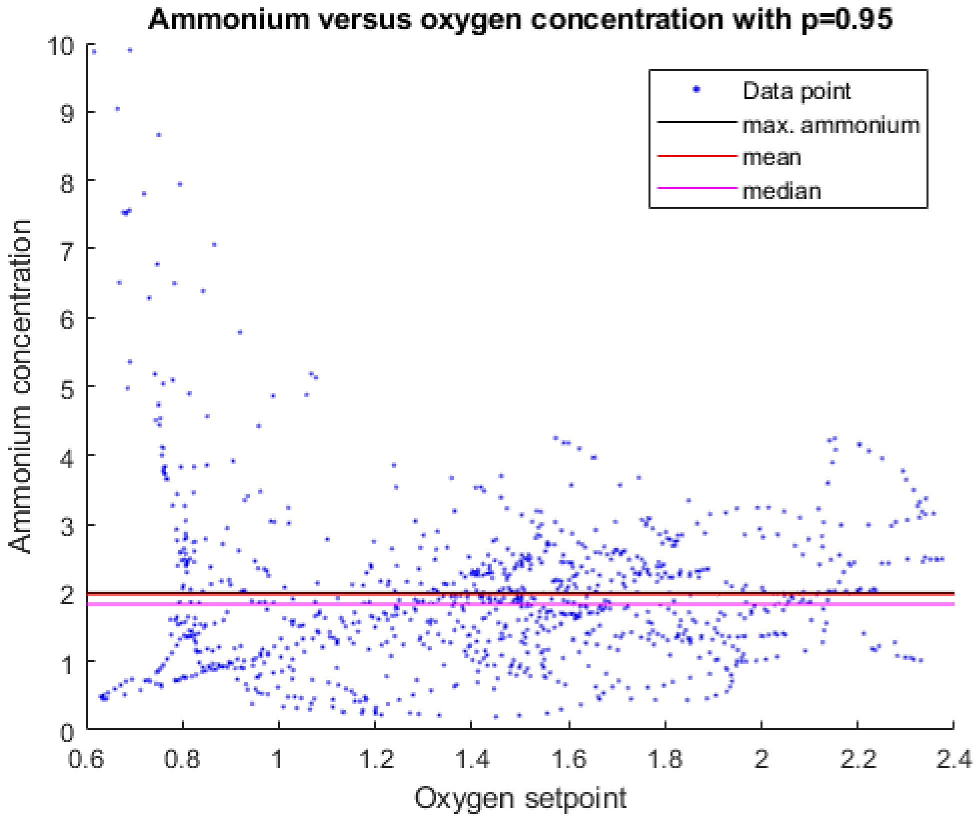


Figure 6.2: Optimal energy oxygen setpoints together with the ammonium levels, with $p = 0.95$.

Finally, we summarized our findings for different values of p in Table 6.1. We also computed the first and third quartile. For completeness the percentage of predicted ammonium concentrations below 2.0 mg/L is also calculated. This gives an indication of the distribution of the ammonium values.

p	0.90	0.91	0.92	0.93	0.94	0.95
Mean	2.1820	2.1381	2.0961	2.0560	2.0175	1.9806
Lower quartile (Q1)	1.3778	1.3502	1.3272	1.3071	1.2794	1.2565
Median (Q2)	1.9808	1.9491	1.9160	1.8897	1.8629	1.8368
Upper quartile (Q3)	2.6394	2.5912	2.5512	2.5103	2.4673	2.4306
Percentage under 2.0 mg/L	50.5%	52.2%	54.0%	55.8%	57.2%	58.3%

p	0.96	0.97	0.98	0.99	1.00
Mean	1.9451	1.9110	1.8781	1.8465	1.8160
Lower quartile (Q1)	1.2322	1.2100	1.1902	1.1697	1.1497
Median (Q2)	1.8056	1.7768	1.7415	1.7134	1.6855
Upper quartile (Q3)	2.3916	2.3504	2.3137	2.2766	2.2444
Percentage under 2.0 mg/L	60.4%	61.7%	63.1%	64.7%	64.9%

Table 6.1: Overview of the set of predicted ammonium concentrations for different values of p.

Chapter 7

Conclusion

In this report, the results of my internship have been documented. We studied the aeration process in the biological treatment plant. In one of the steps of the biological treatment bacteria break down ammonium into nitrate. These bacteria need oxygen in order to perform these reactions. A human supervisor can control the amount of oxygen supplied to the activated sludge tank.

Witteveen+Bos has developed a model-based controller to automate this aeration process, the WOMBAT®, and later on, the advanced WOMBAT®. These controllers continuously steer towards the optimal oxygen setpoint, by which we mean that this is the oxygen setpoint where the amount of total nitrogen is the lowest. The WOMBAT® controllers also predict the ammonium level, and this prediction can be compared to the actual ammonium measurement. The error between the two serves as feedback.

The goal of the internship was to study and improve this model based controller. To that end, we first researched how the level of ammonium compares to the oxygen level. To do so, we studied the Activated Sludge Model (ASM). Unfortunately, the ASM model is a closed vessel model and does not take into account additional inputs and outputs. That is why we moved our attention to a physical model describing the relationship between ammonium and oxygen.

The advanced WOMBAT® makes use of this physical model describing the relation between the ammonium and oxygen concentration. It is assumed that these two quantities are inversely proportional. We have run a data analysis in Matlab using real life recorded data of the Amsterdam Westpoort wastewate treatment plant, and it turned out that this relationship was not present in the measurements. The reason is that the controller keeps the oxygen level within a certain range. Excessive situations where the oxygen concentration is either very low or very high do not occur, because the controller works properly. It is therefore difficult to conclude whether the inversely proportional relationship is present, because we have only datapoints for a small range of oxygen concentrations.

We then investigated the possibility to steer towards a less energy consuming oxygen setpoint. At this oxygen level, less ammonium is broken down into nitrate since less oxygen will be supplied from the aerators, which will save energy hence money. Of course the legal requirements of the Water Framework Directive should still be satisfied.

To this end, we studied a simulation of the advanced WOMBAT® controller in Excel. We showed that it is possible to aerate 5% less than the optimal oxygen setpoint. We suggest to implement this change to the advanced WOMBAT® controller, since we can save up to €3200 annually that way.

For future research it would be nice if we can get our hands on a software package in which a wastewater treatment plant can be simulated (for example: Simba). The updated advanced WOMBAT® controller can then be modeled and put to the test. If the simulation shows promising results, the updated WOMBAT® can be installed on a wastewater treatment plant.

Another direction of future research would be to find exact formulas for the ammonium concentration and total nitrogen concentration, as function of the oxygen setpoint. We tried to do that by using the ASM1 model. A problem we ran into was that we did not know how to incorporate the additional inputs and outputs to the activated sludge tank. For example, it is difficult to add the supplied oxygen from the aerators to the activated sludge tank, because this air is only supplied in the aerated zone of the tank. A possible solution would be to model the activated sludge tank as two tanks: an aerobic tank and a non-aerobic tank. We then have twice as many components, however, the differential equations simplify since not all processes take place in every zone of the activated sludge tank. Also, additional inputs and outputs act only on one of the tanks. If we can find exact formulas for the ammonium and total nitrogen concentrations, we can solve those equations for the optimal energy oxygen setpoint, which is the lowest oxygen concentration possible with the constraints that the ammonium concentration is maximally 2 mg/L and the total nitrogen is at most 10 mg/L. We update the WOMBAT® controller such that it now continuously steers towards this oxygen setpoint.

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Appendix A: Table of ASM1 constants

Below the table of fixed parameters appearing in the ASM1 model is given. The first 5 constants appear in the stoichiometric coefficients, while the other 14 parameters are kinetic constants, appearing in the process rate expressions. The table is taken from [5].

Constant	Description	Type
Y_H	heterotrophic yield	stoich.
Y_A	autotrophic yield	stoich.
f_p	fraction of biomass yielding particulate products	stoich.
i_{XB}	mass of nitrogen per mass COD in biomass	stoich.
i_{XP}	mass of nitrogen per mass COD in products of biomass	stoich.
μ_H	heterotrophic maximum specific growth rate	kin.
b_H	heterotrophic decay rate	kin.
K_S	half-saturation coefficient for heterotrophs	kin.
K_{OH}	oxygen half-saturation coefficient for heterotrophs	kin.
K_{NO}	nitrate half-saturation coefficient for denitrifying heterotrophs	kin.
μ_A	autotrophic maximum specific growth rate	kin.
b_A	autotrophic decay rate	kin.
K_{OA}	oxygen half-saturation coefficient for autotrophs	kin.
K_{NH}	ammonia half-saturation coefficient for autotrophs	kin.
η_g	correction factor for anoxic growth of heterotrophs	kin.
k_a	ammonification rate	kin.
K_h	maximum specific hydrolysis rate	kin.
K_X	half-saturation coefficient for hydrolysis of slowly biodegradable substrate	kin.
η_h	correction factor for anoxic hydrolysis	kin.

Table 7.1: Table of the ASM1 constant, taken from [5].

Appendix B: Functional design advanced WOMBAT®

The functional design of the advanced WOMBAT® controller is confidential information. Please get in touch with Witteveen+Bos if you desire access.