AERATION CONTROL IN ACTIVATED SLUDGE SYSTEMS

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SUMMARY

INTRODUCTION

As the pressure to cover costs and ensure economical operation grows on municipal wastewater treatment plants (WWTP) too, their operational optimization is gaining importance. Measuring and control concepts can help to reduce the variable costs and offer a cost-saving alternative to the extension of reactor volume. However, they contain the risk of violating the effluent limits due to measuring errors, unsuitable control concepts or inadequate applications.

OBJECTIVES

The aim of this study was to investigate the problems occurring in practice in the measuring and control systems of WWTPs. In view of its economic and process importance, the air-supply control system was selected as an example. The following points were to be evaluated:

- The measuring equipment
- The data quality
- The ammonia-based aeration control
- The design of the measuring and control systems
- The technical and socio-economic problems occurring during implementation

METHODOLOGY

The results were obtained from detailed simulation studies on three WWTPs with special demands on the data quality. Full-scale applications were carried out at two WWTPs.

Dynamic simulation is a suitable tool for integrating the knowledge of all the experts involved. A biokinetic model was formulated which allows the biological processes to be predicted. To obtain reliable results from the control behaviour, the time constants of the measuring and control system must also be taken explicitly into account. The sensor and aeration-system models needed for this purpose were developed in this work.

Besides the technical questions, operational aspects were also taken into account. Special emphasis was placed on socio-economic aspects during the full-scale application.

MEASURING EQUIPMENT

Depending on the goal of the measurement, different demands are made on the measuring devices. A short response time is often of major interest for control applications, whereas the accuracy is most important for the effluent monitoring.

In this work, ion-sensitive in-line sensors were applied at different locations and evaluated for control purposes. The advantage of the measuring principle is its minimal response time and applicability at locations where conventional analysers with a filtration unit reach their limits. Among its disadvantages are drift effects and strong cross-sensitivities to disturbance ions. Taking the pros and cons into account, the general applicability of the sensors for aeration control was demonstrated.
DATA QUALITY

On-line measurements form the basis of control systems. To obtain reliable and correctly operating systems, a certain accuracy of the input has to be ensured. The first step is to prevent systematic measuring errors and the second step is to calculate the uncertainties of the instruments. A knowledge of the uncertainties involved allows the required safety factors to be calculated, which in turn permits optimal controller parameterization.

During this work, a monitoring concept was developed which uses comparative measurements and allows measuring errors and poor calibration to be identified. The concept was implemented in a software environment and was successfully tested in various plants in Switzerland. In addition, a procedure designed to calculate the uncertainties of on-line sensors is proposed.

AERATION CONTROL

In Switzerland, the most common control goal is to keep the oxygen concentration at a fixed level and not to regulate the air supply according to the demands of the purification processes. In contrast, ammonia-based control enables aeration tailored to the requirements. Within this work, different control strategies are tested by simulation and in full-scale operation. The best strategy to be selected will depend on the kinds of diffusers, the specific constraints of the plant and the optimization goal. If the main goal is to reduce the energy consumption, a DO set-point adjustment due to the ammonia concentration often makes good sense, whereas an on-off control of the blower unit has the advantage of increasing the total nitrogen elimination because the control power is often higher.

In the simulation studies, a feed-forward control part was included in the aeration control strategy. These concepts can trigger control actions based on information about process influences before a reaction can be observed. This will allow the influence of predictable disturbances to be minimized and effluent peaks to be reduced.

DYNAMIC SIMULATION

Dynamic simulation is a proven tool for predicting the behaviour of a WWTP with the required accuracy. To obtain realistic results for the control actions too, the time constants of the system must be taken explicitly into account. Models for the sensors and the aeration system were consequently developed in addition to a biokinetic model.

Two groups of sensor models are proposed:

- Specific models which can be calibrated to existing sensors.
- A classification system which is intended for design studies.

The aim of the first group is to model and optimize existing measuring and control systems. The classification system was devised to obtain more realistic and comparable design studies. The models are divided up into continuously and discontinuously operating ones and take into account the response time, simplified and standardized noise and the measuring interval. The specific models are enhanced by drift effects as well as calibration and cleaning intervals.

To design, compare or evaluate different types of air-supply controllers under conditions close to reality, it is necessary to differentiate between the controlled system, the controller, the sensor and the aeration system. The aeration system is modelled as a response time of the air supply. Before the model can be calibrated, a validated model must be available for the oxygen transfer, since the parameters for the oxygen transfer and the time delay are strongly correlated.
The biokinetic model is an enhancement of the well-known ASM3 and can predict the oxygen consumption, sludge production, nitrification, denitrification and enhanced biological phosphorus removal. The model was systematically calibrated with experimental data from various batch experiments, a full-scale WWTP and a pilot plant. A standard parameter set allowed all the data to be simulated.

SOCIO-ECONOMIC EXAMINATION

Socio-economic aspects were identified as an important reason why measuring and control systems do not operate in a satisfactory manner over a prolonged period. The reservations held against new control concepts could be linked to differing interests and a lack of sufficient incentives. The chain of incentives in Switzerland from the federal agency for the environment down to the plant operator is discussed and recommendations suggested. Major incentives for optimized aeration control are created by an effluent-load tax which is applied in only two cantons in Switzerland. At plant level, it is most important to integrate the operators from the beginning and to give them enough incentives for the extra work required by the newly installed measuring and control systems. During the design phase, the knowledge of the experts involved must be made available and integrated in the control strategy. Dynamic simulation represents an optimal tool for knowledge integration with respect to control.

CASE STUDIES

The results were obtained from detailed simulation studies on three WWTPs (35,000 p.e., 130,000 p.e. and 600,000 p.e.) and full-scale applications on two of them. The simulation results show that aeration-control concepts based on ammonia can lead to a significant reduction of energy consumption (25-30%) and total nitrogen discharge (30-55%). At nitrifying plants, the introduction of ammonia-based aeration control can release free capacities for denitrification and - at least temporarily - for enhanced biological phosphorus removal (Bio-P). If the Bio-P processes are already in use, the reduced aeration increases the phosphorus removal efficiency. This increases the cost reduction potential due to less precipitant consumption and therefore decreased production of precipitant sludge requiring disposal.

In principle, the full-scale results validated the reduction potential of the simulation studies. However, the technical, operational and political constraints of the plants prevented the application of the best-rated control concepts obtained by the simulation studies. Nevertheless, the reduction in energy consumption was 20% and 16% for WWTP Morgental and WWTP Thunersee respectively. The nitrogen discharge could be simultaneously decreased by 40% at both plants.

During the full-scale applications, the following practical aspects were evaluated:

- The effort for monitoring and maintaining the sensors (1-3 h/week and device)
- The effect of peak consumption on the energy price (as distinct from the cost reduction due to the lower average aeration)
- The cost drawbacks due to filamentous growth and foam formation (no direct influence by the control strategies on this formation was observed)
- The increase of nitrite in the effluent due to low oxygen concentrations (no sustained influence was measured here either)
ZUSAMMENFASSUNG

EINLEITUNG
Mit zunehmendem finanziellem Druck nimmt die Bedeutung einer kostendeckenden und sparsamen Betriebsführung auch auf kommunalen Kläranlagen immer stärker zu. Die Mess-, Steuer- und Regelungstechnik (MSR) kann helfen, die variablen Kosten zu minimieren und ist eine Kosten sparende Alternative zur Erweiterung der Beckenvolumina. Auf der anderen Seite muss das Risiko von Überschreitungen der Ablaufgrenzwerte berücksichtigt werden, die durch Fehlmessungen, untaugliche MSR-Konzepte oder ungeeignete Umsetzungen entstehen können.

ZIELSETZUNG
• Messtechnik
• Datenqualität
• Ammonium basierte Steuerungen und Regelungen
• Planung von MSR-Systemen
• Technische und sozioökonomische Probleme bei der Umsetzung

VORGEHEN
Detaillierte Simulationsstudien auf drei verschiedenen Kläranlagen bildeten die Basis für die spätere grosstechnische Umsetzung auf zwei der Anlagen, wobei besondere Anforderungen an die Datenqualität gestellt wurden. Ein geeignetes Werkzeug, um das Wissen aller beteiligten Experten zu integrieren, ist die dynamische Simulation. Das benötigte biokinetische Modell und die Modelle für die Sensoren und das Belüftungssystem wurden im Rahmen der Arbeit entwickelt. Neben den rein technischen Fragen wurde ein Schwerpunkt auf betriebliche Aspekte bei der praktischen Umsetzung gelegt. Ebenfalls sollten sozioökonomische Fragestellungen bei der Umsetzung der MSR-Konzepte einbezogen werden.

MESSTECHNIK
Abhängig vom Ziel der Messung bestehen unterschiedliche Anforderungen an die Messgeräte. Für Anwendungen in der MSR-Technik ist oftmals eine kurze Ansprechzeit der wichtigste Faktor, wohingegen für die Ablaufüberwachung die Genauigkeit die grösste Bedeutung hat.

DATENQUALITÄT

Online-Messungen sind die Basis von MSR-Systemen. Um zufrieden stellende und zuverlässig arbeitende MSR-Systeme zu erhalten, ist eine bestimmte Genauigkeit der Messungen erforderlich. Ein erster Schritt ist, systematische Fehler zu verhindern; ein zweiter Schritt ist die Quantifizierung der Unsicherheiten des Messgerätes. Sind die Unsicherheiten bekannt, können die benötigten Sicherheitsfaktoren bestimmt werden, was eine optimale Reglerkonfiguration erlaubt.

Im Rahmen der vorliegenden Arbeit wurde ein Überwachungskonzept entwickelt, das auf Vergleichsmessungen basiert und die Identifikation von systematischen Messfehlern und einer fehlerhaften Kalibrierung erlaubt. Das Konzept wurde in einer Software-Umgebung umgesetzt und auf verschiedenen Anlagen in der Schweiz erfolgreich getestet. Zusätzlich wurde ein Konzept integriert, welches die Unsicherheiten der Messgeräte im Betrieb kalkuliert.

BELÜFTUNGSREGELUNG


In den Simulationsstudien wurde zusätzlich eine Vorsteuerung in die Regelungsstrategien integriert. Dieses Konzept kann die Anlage frühzeitig an Belastungsschwankungen anpassen noch bevor eine Prozessreaktion feststellbar ist. Hierdurch können Einflüsse von vorhersagbaren Störeinflüssen minimiert und somit Ablaufspitzen reduziert werden.

DYNAMISCHE SIMULATION


- Spezifische Modelle, die auf vorhandene Sensoren kalibriert werden können.
- Ein Klassifizierungssystem, das für Design-Studien gedacht ist.


**SOZIOÖKONOMISCHE ASPEKTE**


**FALLSTUDIEN**

Die Resultate von detaillierten Simulationsstudien auf drei Kläranlagen (35’000, 130’000 and 600’000 EW) zeigen, dass Ammonium basierte Belüftungskonzepte zu einer signifikanten Reduktion des Energieverbrauchs (25-30%) und der Stickstoff-Eliminationsleistung (30-55%) führen. Auf nitrifizierenden Anlagen ermöglichen die neuen Regelkonzepte die Nutzung von freien Kapazitäten für die Denitrifikation und eventuell – zumindest zeitweise – für die Einführung einer biologischen Phosphor-Elimination (Bio-P). Wenn die Anlage bereits Bio-P einsetzt, kann die Leistung deutlich gesteigert werden. Dies vergrößert die Einsparpotentiale durch reduzierten Fällmitteleinsatz und dadurch weniger Produktion von Fällschlamm, der teuer entsorgt werden müsste.

Prinzipiell bestätigen die grosstechnischen Resultate die Einsparpotentiale der Simulationsstudien, allerdings verhinderten technische, betriebliche und politische Rahmenbedingungen die Umsetzung der am besten bewerteten Varianten aus den Simulationsstudien. Nichtsdestotrotz konnten grosstechnische Energieeinsparungen von 20% (ARA Morgental) und 16% (ARA Thunersee) erzielt werden. In der gleichen Zeit sank die Stickstoff-Ablauffracht bei beiden Anlagen um 40% gegenüber dem Grundzustand. Während der Umsetzung wurden zusätzlich die folgenden betrieblichen Aspekte untersucht:

- Aufwand für die Kontrolle und Wartung der Messgeräte (1-3 h/Woche und Gerät)
- Einfluss von Spitzenverbräuchen auf den Energiepreis (im Unterschied zur Kostenminderung durch niedrigere mittlere Belüftung)
- Kostennachteile durch fadenförmige Organismen und Schaumbildung (es konnte kein direkter Einfluss durch die MSR-Konzepte beobachtet werden)
- Erhöhte Nitrit-Ablaufwerte bei niedrigen Sauerstoffgehalten (es konnte ebenfalls kein dauerhafter Einfluss festgestellt werden)
CONTENTS

Summary iii

Zusammenfassung vii

General Introduction 1

Chapter 1: In-situ measurement of ammonium and nitrate in the activated sludge process 11

Chapter 2: Computer aided monitoring and operation of on-line measuring devices 23

Chapter 3: Quantifying the uncertainty of on-line sensors at WWTPs during field operation 35

Chapter 4: Progress in sensor technology – progress in process control?
Part I: Sensor property investigation and classification 51

Chapter 5: The EAWAG Bio-P module for activated sludge model no. 3 63

Chapter 6: Modelling of air supply systems at wastewater treatment plants 87

Chapter 7: Socio-economic aspects 99

Chapter 8: Case studies 109

Conclusions 137

Outlook 143

Curriculum Vitae 147
GENERAL INTRODUCTION
General Introduction

In recent years, priority has been given to performing cost evaluations in order to reduce investment costs for new plants or for enhancements of existing plants. In future, however, interest will centre on optimizing plant operation and in particular on controlling the biological processes in conjunction with the consumption of energy and chemicals. Measuring and control concepts are a cost-saving alternative to the extension of reactor volume. However, they also involve the risk of violation of the effluent limits due to measuring errors, unsuitable control concepts or inadequate implementation of the measuring and control system.

The implementation of measuring and control systems in wastewater treatment plants (WWTP) is still a difficult task in practice. Whereas sophisticated control strategies are discussed in the academic community, numerous problems arise in full-scale plants while attempting to operate even the simplest control concepts and particularly to keep the system running. This is due to technical problems, stemming mainly from the measuring equipment, and to socio-economic constraints. The latter result from low acceptance of these systems by the plant staff as a result of inadequate incentives or a lack of knowledge of the processes involved. Urgently needed quality-control concepts for the measuring devices do not exist or are inefficient in daily operation despite the fact that measurements are the input for control loops and the basis for quantifying the benefits of a measure. The design of the control system is often not adapted to the plant in question or the controllers were designed by process engineers without integrating a knowledge of control engineering.

This dissertation investigates the main problems arising when aeration control systems in the biological stage of WWTPs are applied in practice and proposes solutions which are applicable to the plants. To overcome the problems of inaccurate data, a concept is proposed to increase the efficiency of the quality control applied to the measuring equipment. Simulation is a suitable tool for optimizing the design process with respect to the dynamics of the measuring and control systems. The required models of the biological, sensor and aeration systems are developed and validated.

NITRIFICATION VERSUS DENITRIFICATION VERSUS ENERGY CONSUMPTION

Nitrogen and phosphorus are essential for the growth of all organisms. In the course of wastewater treatment, there are two reasons for removing them from the effluent: firstly if the component consumes oxygen or is toxic to organisms in the receiving water, and secondly if the compound is involved in eutrophication.

Swiss effluent limits are very restrictive with respect to phosphorus because it is the limiting factor for eutrophication in most inland waters in Switzerland. Phosphorus can be eliminated by chemical precipitation or enhanced phosphorus removal (Bio-P). Although chemical precipitation is sufficiently effective and is common in Switzerland, the Bio-P process has advantages with respect to chemical consumption as well as sludge production and disposal.

Enhanced biological nitrogen removal is the main topic of this thesis and can be divided into nitrification and denitrification. In the nitrification process, ammonia (NH₄) is oxidized by autotrophic micro-organisms, first to nitrite (NO₂) and then to nitrate (NO₃). During the denitrification process, heterotrophic micro-organisms use nitrate instead of oxygen as the electron acceptor to oxidize organic matter. The denitrification converts nitrate to elementary nitrogen (N₂).
General Introduction

If ammonia is discharged into a body of water (e.g. due to lacking or inadequate nitrification), the oxygen respiration increases. Depending on the kind of water involved, this can lead to a DO deficiency that damages water organisms. At high pH values, the ammonium/ammoniac equilibration shifts to ammoniac (NH$_3$), which is toxic to fish.

Nitrite (NO$_2$) is an intermediate product of the two-step process of nitrification. Because the second nitrification step is very fast, the nitrite concentration in the effluent of a WWTP is normally very low (around 0.1 mg/l). Enrichment of nitrite in the system usually suggests that the microbiological processes are disturbed or the plant is overloaded. This implies inhibition due to toxic substances or to unfavourable conditions for the nitrite oxidiser. Nitrite is a powerful poison for fish; it reduces the oxygen transfer capability of the blood. High concentrations of nitrite in the effluent of WWTPs can produce damage in organisms if its dilution in the body of receiving water is too low.

A discharge of nitrate can cause eutrophication. In most inland waters, phosphorus is the limiting nutrient, but in estuaries and shallow coastal waters nitrogen is recognized as the limiting factor for algae growth (such as in the North Sea). Eutrophication leads to changes in the food chain due to the destruction of established habitats and finally to a shift in the population with unforeseeable consequences for the environment.

In most cases, the energy needed to run a WWTP can be generated only partly from resources within the plant. A certain amount of energy has to be obtained from an external supplier. Since energy production can also pollute the environment, the source of the energy and its consumption has to be taken into account during an optimization. To concentrate only on the quality of the receiving water will merely shift the problem from water to air pollution or to waste disposal.

EUROPEAN AND SWISS REGULATIONS FOR NITROGEN ELIMINATION

With regard to nitrogen removal, in Switzerland priority is given to nitrification. This has resulted in an ammonia effluent limit for sensitive areas (rivers) of 2 mg N/l in the 24h composite sample and an ammonia removal rate of at least 90%. The Swiss regulations recommend that as much nitrogen be removed as possible (GSchV, 2003). Although Swiss eutrophication is due only to phosphorus, Switzerland is a signatory to an international agreement designed to reduce the nitrogen load entering the North Sea via the river Rhine. Selected WWTPs in the Rhine catchment area must improve their operation in order to reduce the total mass of nitrogen released from Switzerland by 2600 tons annually by the year 2005 compared to 1995.

According to a study from 1996 (BUWAL, 1996), only 20% of Swiss wastewater was treated in nitrifying plants. Since then, most of the larger WWTPs have been upgraded for nitrification and most often also for denitrification. Although no actual data exists, a rough estimate shows an increase of nitrifying WWTPs to ca. 50% in the last 8 years. Since the solids retention time and aeration capacity are sufficient only at nitrifying plants, the discussion of aeration control strategies will be limited to these plants.

The European Union stipulates (as per EC Directive 91/271/ECC modified 1998) that 70 – 80% of the nitrogen must be removed in treatment plants above 100,000 population equivalents (p.e.) in nutrient-sensitive zones. The implementation of this directive has led to different national regulations in neighbouring countries. In Germany, for example, it has produced a tightening of the effluent-quality regulations for total nitrogen (Bundesgesetzblatt, 2002). Whereas the German regulations are based only on measurements of the concentration in the effluent, the
European purification limits require additional influent measurements. So the limits had to be reduced from 18 to 13 mg N/l in order to guarantee the stipulated nitrogen elimination. In Austria, the ammonia limits are set at 5 mg N/l (temperature ≥ 8°C) and an efficiency of 70% (temperature ≥ 12°C) has to be achieved for total nitrogen.

**MEASURING EQUIPMENT – THE LIMITING FACTOR**

Experience gained during full-scale implementations showed that the measuring devices – as the input to the control loops – are still the limiting factor for both sophisticated and basic aeration control. The main problem is to guarantee reliable and accurate measurements over the lifetime of the devices. The required sensors should operate with low maintenance and generate low investment and operating costs in relation to the achievable benefit.

These devices are of two types, namely on-line analysers (mostly with a filtration unit) and in-situ or in-line probes. On-line analysers have the advantage of allowing auto-calibration routines to be implemented, whereas in-line sensors perform their measurements directly in the liquid without the need for time-consuming pumping and filtration. A trend can be observed in favour of using in-line probes for control applications because the response time, which is an important source of control errors, is greatly reduced in comparison with classical on-line analysers equipped with a filtration unit.

**QUALITY CONTROL**

In recent years, numerous sensors designed specifically for nutrients have been developed and put on the market, but there is still a lack of suitable monitoring concepts. If the measuring devices are maintained and monitored in a sensible way, their accuracy, reliability and acceptance will be greatly increased. Moreover, it will also be possible to assess the uncertainty, operating time and costs of the sensors.

**Detection of systematic errors**

Experience gained during the work on this thesis showed that there is major need for a monitoring concept which can be used by the plant staff with a minimum of monitoring effort but with a high probability of detecting systematic errors. A monitoring concept has been developed in line with these requirements (Thomann et al., 2002 and Rieger et al., accepted).

**Quantification of the uncertainty**

In addition to a monitoring concept for detecting systematic errors, a method is required to quantify the uncertainties of the continuously measuring devices during field operation. Commonly used methods are based on lab experiments under standardized conditions and are only suitable for the measuring device itself and not the entire measuring chain. For measuring devices under field conditions, a knowledge of the response time is as important as differentiation between trueness and precision. Information about the trueness and precision of the measuring system under field conditions helps to adapt control strategies more effectively to the relevant processes and permits sophisticated control concepts to be applied. Moreover, the concept can help to define guidelines for evaluating the uncertainties involved in monitoring effluent quality. This will greatly increase the acceptance of the measuring devices and of continuous effluent-quality monitoring within the control system.
AERATION CONTROL

In Western Europe DO control in the activated sludge tanks is state-of-the-art and implemented in most WWTPs. The nitrification and denitrification stages can be differentiated by operating separated tanks under different DO conditions or applying a time-based aeration in the same reactor. In Switzerland, the nitrification/denitrification plants are usually built with fixed reactor volumes. Conventional upgrading of WWTPs for the introduction or increase of denitrification normally leads to cost-intensive extensions of reactor volume or introduction/enlargement of fixed anoxic zones. The substantial investment costs involved could be significantly reduced by separate treatment of the ammonium-rich digester supernatant (Fux, 2003) or by using control measures based on an indicator for compounds causing high oxygen respiration. In nutrient removal plants with sludge retention times above 8d, this is mainly ammonia. A time-based distinction between nitrification and denitrification via ammonium instead of the use of fixed volumes allows more flexible control strategies to be implemented.

DO CONTROL

In the common set-up of a Swiss WWTP designed for nitrification, the DO is controlled at a fixed level of around 2 mg DO/l. The nitrified sludge is recycled via the return sludge (or additionally by means of an internal recycle) to the denitrification zone (pre-denitrification). The design of the reactor volumes is static with respect to a mean loading, taking into account safety factors for nitrification under conditions of peak loading. The result is a plant that nitrifies completely but also aerates if little or no ammonia is present in the reactor. This leads to unnecessary energy consumption and prevents the additional elimination of nitrogen from the normally aerated zones.

AMMONIA CONTROL

Measuring and control concepts allow the aeration to be adapted to the specified requirements. At low loadings the aeration can be reduced to a minimum or switched off completely. An ammonium sensor is required at the end of the aerated zone to measure the oxygen respiration. The advantage of an ammonia control loop is that only the amount of ammonia is nitrified which is needed to meet the regulation limits defining the current environmental requirements. Below an ammonia set point, the oxygen input is decreased and capacity is created for enhanced denitrification. At the same time, the reduced aeration leads to a clear reduction in energy consumption. Since the aeration accounts for some 60% of the energy consumption of a WWTP, this also reduces the operating costs significantly.

IMPLEMENTATION

The behaviour of an aeration control system depends on the dynamic characteristics of:

- the processes involved (biological processes causing oxygen respiration, oxygen input, hydraulic processes, etc.),
- the actuators (such as valves, blower, etc.),
- the measuring equipment, and
- the controller (type and parameters).

These properties must be included in the design and parameterization of a measuring and control system.
A first step in the implementation of a controller is to select the optimal control algorithm for the relevant case. In the WWTP planning process, the controller is often not selected by a control engineer but is defined by the process engineer on the basis of his experience or pre-determined guidelines. A problem can arise if the notation inevitably leads to a particular kind of controller which is not suitable for the control task.

When the technical implementation has been performed, the controller must be parameterized. There are many static design rules which give a first hint as to the parameter settings, but they are unsuitable for predicting the dynamic behaviour. In the industrial sector, fine-tuning is still a task for a highly specialized and expensive control engineer who adjusts the controller manually, largely on the basis of his experience. In the wastewater sector, this specialist work is normally too expensive and is therefore neglected.

**DYNAMIC SIMULATION – A SUITABLE TOOL**

The dynamic simulation of activated sludge systems is an accepted tool in wastewater research and has also proved its usefulness in practice. It is used to increase the process knowledge, to optimize operations or processes, to design process concepts or measuring and control systems. Thanks to the compressed process knowledge it contains, it is eminently suitable for training operators and teaching engineers. The application of model-based predictive control (MPC) has recently been widely discussed (e.g. Weijers, 2000): MPC predicts the purification efficiency on the basis of influent measurements and calculates optimal settings for the actuators.

Existing models are highly over-parameterised, but their broad application (mainly of the ASM1) has led to reliable sets of parameters, at least for municipal WWTPs. The greatest uncertainty is no longer due to the models but to the database used or to insufficient calibration at plant level. On the basis of this experience, a group of researchers has defined a guideline for simulation studies (Langergraber et al., 2004). Other guidelines or protocols can be found in Hulsbeek et al. (2002), Petersen et al. (2001), and LUA-NRW (1998). An extensive overview of methods for wastewater characterization is given by a WERF report (WERF, 2003).

The advantages of a dynamic simulation are that knowledge of the complex processes can be made available in compressed form. As regards the dynamic behaviour, even temporal free capacities can be recognized and quantified. The tool allows extensive studies of different scenarios without expensive and time-consuming experiments on a pilot scale. The scenarios can be compared under specified and identical loading conditions, and critical situations can be defined and evaluated. Moreover, slow control loops (time constants of several days) can then be tuned.

Dynamic simulation is also a suitable tool for overcoming the problems of controller design and parameterization mentioned above: from a control-engineering point of view, the characterization of the controlled system is the critical task because the control engineer will normally not have a knowledge of the relevant processes and conditions. The process engineer has limited experience of controller design and as a rule only little information about the measuring device. A dynamic simulation represents a suitable tool for integrating the knowledge of process and control engineers. Reliable models are available for the biological processes (e.g. the ASM family of models: Henze et al. 2000). The control engineer can contribute controller models and methods to characterize the additional time constants. The sensors and the aeration system represent the main influence in terms of time delays (Rieger et al., 2003; Alex et al., 2003). Taking the different time constants explicitly into account allows a better off-line parameterization which saves design effort and time.
General Introduction

SOCIO-ECONOMIC EXAMINATION

The interplay between the specialists involved in the design process is often characterized by a lack of information exchange and knowledge about their respective other fields. It should be organized in such a way that all relevant knowledge is available to all participants.

For a fairly long-term application of the control loops it is essential to integrate the operators from the outset and to communicate at least the basic process-control background. Problems arise from the low priority given to these systems by the plant staff as a result of inadequate incentives, the overwhelming pressure of daily business as well as a lack of sufficient knowledge of the processes involved.

OBJECTIVES

The aim of this study is to investigate the main problems occurring in the application of aeration control systems for the biological stage of WWTPs in practice and to propose solutions which can be applied to the plants. To overcome the problem of inaccurate data, a concept will be proposed to make the quality control of the measuring equipment more efficient. The data will also be used to quantify the uncertainties arising during field operation. Dynamic simulation is a suitable tool for optimising the process of designing the measuring and control systems. The requisite biological, sensor, controller and actuator models will have to be developed and validated. Socio-economic aspects turn out to be one of the most important reasons as to why control concepts do not work efficiently in practice. Although this is not the main objective of this work, some conclusions about this topic will be drawn.

The work aims to make a contribution to reducing the gap between research and practice.
OUTLINE OF THE THESIS

Suitable ammonia sensors: low-cost ammonia sensors have to be found as a suitable means of aeration control which satisfies the requirements of the process optimum and the energy consumption. They may be applied in the activated sludge (for feed-back control) and in the effluent of the primary clarifier (feed-forward control). A short response time is important for control applications. The first chapter presents the experience gained with ion-sensitive sensors for ammonia and nitrate.

Developing a monitoring concept for use on WWTPs: there is still a lack of suitable and efficient monitoring concepts for on-line sensors which can detect drift, shift and outliers as well as poor calibration. An efficient concept for practical use implemented in a software environment is described in the second chapter.

Quantifying uncertainties: in addition to the detection of systematic errors, the uncertainty of on-line sensors during field operation must be quantified for optimal controller parameterization as well as reliable effluent-quality monitoring. The third chapter includes a method of quantifying the uncertainty on the basis of comparative measurements.

Sensor models: dynamic simulation is a suitable tool for the design and optimization of measuring and control systems. To obtain sufficiently accurate results for an off-line parameterization of controllers, the time constants and behaviour of the sensors have to be included in the model. In chapter four, different sensor models are proposed. Optimization studies require specific sensor models which take the response time, the measuring noise and the measuring interval into account. For design tasks in which no data about specific devices is available, various sensor classes will be defined. This classification system allows the demands of the control system on the measuring devices to be defined.

Bio-kinetic model: the main part of a dynamic simulation study is of course the bio-kinetic model. In chapter five a model is developed and calibrated for activated sludge systems which mainly treat municipal wastewater. The model can predict oxygen consumption, sludge production, nitrification, denitrification and enhanced biological phosphorus removal.

Modelling of air-supply systems: to parameterize controllers off-line via dynamic simulation, the time constants of the air supply system must also be integrated in the model. In chapter six a concept will be shown which enables the model to be calibrated by using simplified models for oxygen input and respiration. Additional experiments will be proposed to obtain the required data.

Socio-economic aspects: apart from the more technical parts, the plant operators are the major influence on the sustainable operation of the measuring and control systems. If the operators do not have a good knowledge of the controllers and sensors used, and lack suitable incentives, a measuring and control system will never give optimal results over a longer period of time. In chapter seven some socio-economic aspects are discussed.

Case studies: Chapter eight focuses on case studies at WWTP Morgental, WWTP Thunersee and WWTP Werdhoelzli. It could be shown that ammonia-based aeration control results in lower energy consumption in parallel with improved nitrogen elimination. An extrapolation of the cost and environmental benefits for all of Switzerland will complete the studies.

Some major results of this thesis are briefly summarized in the conclusion section. An outlook on possible future research areas is given in the last chapter.
REFERENCES


CHAPTER 1

IN-SITU MEASUREMENT OF AMMONIUM AND NITRATE IN THE ACTIVATED SLUDGE PROCESS

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Suitable Ammonia Sensors

In-situ Measurement of Ammonium and Nitrate in the Activated Sludge Process

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ABSTRACT

A new in-situ probe is presented for the continuous measurement of ammonium and nitrate in wastewater. It requires no sample preparation and is installed directly in the process liquid. This new low-cost probe significantly reduces investment and operating costs and requires minimum maintenance. The paper describes the sensor principle and test results from three different probe locations: the primary clarifier effluent, the activated sludge tank and the nitrifying biofilter influent. Reference measurements were carried out by means of conventional analyzers with ultrafiltration, an in-situ UV spectrometer for the nitrate and laboratory analysis of spot and 2h-composite samples. The aim of the study was to investigate the operational reliability and accuracy of the new probe and the expenditure required for its maintenance and calibration. The tests showed that the new probe performed very well overall and required minimum maintenance. Some problems were observed during the biofilter plant test. They are assumed to be related to substantial changes in the wastewater composition.

KEYWORDS

Ammonium, in-situ measurement, low-cost sensor, maintenance, nitrate, on-line analysis

INTRODUCTION

Research work in the field of ion-sensitive sensors has been conducted at the ETH Zurich over the last 20 years. The results of this work have recently been utilized for the development of online sensors suitable for application in wastewater treatment plants. These new low-cost sensors can measure ammonium and nitrate continuously in the activated sludge process and do not require prior sample preparation, thus simplifying operation significantly in comparison to conventional analyzers.

TECHNICAL DESCRIPTION

THEORETICAL BACKGROUND

The operating principle of the sensor is based on analyzing the potential difference between a reference electrode and a measuring electrode whose potential is sensitive to specific ions. The measuring electrode is equipped with a membrane made of a special polymer that confines the compounds which react with specific ions in the liquid by means of reversible ion exchange. This reaction causes a change in the potential at the interface between the sensor membrane and the liquid to be analyzed. This change in potential difference is a logarithmic function of the ion concentration in the liquid. The influence of interfering ions is given in Table 1. More
Suitable Ammonia Sensors

information on the measurement principle can be found in Amman (1986), Cammann and Galster (1996), and Honold and Honold (1991).

SENSOR CONSTRUCTION

The new probe is constructed as a polymer tube (Ø 70 x 1200 mm) with a signal transformer box at its head end and the respective sensors and reference electrode at its bottom end. All the electronic devices used to control the operation of the probe (calibration, cleaning interval) and to transform the signals are integrated into the signal transformer box so that the new probe can be linked directly to the plant supervision system. A local control panel can be optionally installed. To be installed, the probe requires only connection of the power supply and a water hose. The main technical data of the ammonium and nitrate sensors is summarized in Table 1.

Table 1: Technical data of ammonium and nitrate sensors (manufacturer information)

<table>
<thead>
<tr>
<th></th>
<th>Ammonium sensor</th>
<th>Nitrate sensor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measuring principle</td>
<td>Potentiometric measurement</td>
<td>Potentiometric measurement</td>
</tr>
<tr>
<td>Measuring method</td>
<td>Ion-sensitive ammonium electrode (ionophore)</td>
<td>Ion-sensitive nitrate electrode (ionophore)</td>
</tr>
<tr>
<td>Measuring ranges</td>
<td>0.1 – 1000 mg NH₄-N/l</td>
<td>0.2 – 7000 mg NO₃-N/l</td>
</tr>
<tr>
<td>Resolution</td>
<td>1 mg/l (100-1000 mg NH₄-N/l)</td>
<td>0.1 mg/l</td>
</tr>
<tr>
<td>Sensitivity with respect to other ions</td>
<td>Potassium: 1:100</td>
<td>Chloride: 1:200</td>
</tr>
<tr>
<td></td>
<td>Sodium: 1:1000</td>
<td>Nitrite: 1:100</td>
</tr>
<tr>
<td>Lifetime of the membrane</td>
<td>3–12 months (in activated sludge, the membrane should be exchanged every 3 months)</td>
<td>3–12 months (in activated sludge, the membrane should be exchanged every 3 months)</td>
</tr>
</tbody>
</table>

ISO/CD 15839 (2000) specifies a procedure for testing on-line sensors. Their response time, coefficient of variation, repeatability and trueness as well as the linearity of the calibration curve were analyzed with experiments (for more details see Thomann et al., 2001). Table 2 shows the results of a calibration experiment with standard calibration samples for the investigated ion-
suitable ammonia sensors. Because the potential is influenced by the ionic strength and the matrix of the measuring liquid, a standard addition with a primary effluent sample was also performed.

Table 2: Results of calibration experiments with standard and matrix calibration samples for an ion-selective $\text{NH}_4^+$ sensor (Thomann et al., 2001)

<table>
<thead>
<tr>
<th>Performance Characteristic</th>
<th>Unit</th>
<th>Results according to ISO/CD 15839 (2000)</th>
<th>Standard calibration samples</th>
<th>Matrix calibration samples</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>(NH$_4^+$ reference solution + nanopure water)</td>
<td></td>
<td>(Addition of NH$_4^+$-reference solution to wastewater)</td>
</tr>
<tr>
<td>Response time [sec]</td>
<td></td>
<td>&lt; 5</td>
<td></td>
<td>&lt; 5</td>
</tr>
<tr>
<td>Linearity (tested range) [mgN/L]</td>
<td></td>
<td>4.7 - 32.6</td>
<td></td>
<td>7.0 - 32.0</td>
</tr>
<tr>
<td>Coefficient of variation [%]</td>
<td></td>
<td>1.8</td>
<td></td>
<td>1.4</td>
</tr>
<tr>
<td>Repeatability (at lower end)</td>
<td>[mgN/L]</td>
<td>0.1</td>
<td></td>
<td>0.1</td>
</tr>
<tr>
<td>Repeatability (at higher end)</td>
<td>[mgN/L]</td>
<td>0.2</td>
<td></td>
<td>0.3</td>
</tr>
<tr>
<td>Trueness (at lower end)</td>
<td>[mgN/L]</td>
<td>-0.1</td>
<td></td>
<td>-0.1</td>
</tr>
<tr>
<td>Trueness (at higher end)</td>
<td>[mgN/L]</td>
<td>-0.1</td>
<td></td>
<td>-0.3</td>
</tr>
</tbody>
</table>

Costs and Expenditure

The maintenance effort is comparatively small for the new probe. Only the sensor membrane and the internal electrolyte have to be renewed every three months, a task which requires approximately 15 minutes. The probe is currently not equipped with an automatic calibration system, so the calibration settings should be checked every week. An increased maintenance effort was necessary only at a single test site (the biofilter plant) due to failure of the sensor electronics.

As regards the routine maintenance of conventional ammonium analyzers, the effort required for servicing the probe filtration system and the analyzer must be considered. This includes the periodic refill of chemicals, cleaning and changing of tubes and – if applicable – cleaning and changing the ultrafiltration units. Interviews of plant operators revealed an estimated workload of one hour per week per analyzer. Oennerth et al. (1996) quote a maintenance effort of about 2-5 hours per week for a group of three analyzers (ammonia, nitrate and phosphate).

The total cost of maintenance and spare parts for the new probe can be estimated to be in the range of 5% of the cost of conventional systems. This assumes that both systems work properly and excludes any increased service requirement due to malfunction of any of the systems. The operating costs of conventional analyzers include personnel costs, the cost of spare parts and chemicals and the pumping cost for the sample filtration unit. For instance, the energy requirement for the filter supply pump of an ultrafiltration unit can be estimated as 10000 to 25000 kWh/year.

Probe Locations

A high content of fatty and greasy components in the plant influent or precipitation products behind a precipitant dosage station often creates problems in filtration units. These substances lead to a build-up of coating layers or biofilm there, thus causing measuring errors and increasing the cleaning effort. Continuous measurement of ammonium at these sampling locations was therefore a critical task. Because the new probe does not require sample preparation, it can also be applied at the influent or effluent channel of a primary clarifier.

Results and Discussion

The aim of the probe test was to investigate the operational reliability and accuracy as well as the maintenance and control expenditures of the new probe. It was consequently applied at different
Suitable Ammonia Sensors

locations at WWTPs in Switzerland and Austria. Except for the test at the biofilter plant, no manual cleaning was performed in order to investigate the performance of the automatic cleaning device. Table 3 shows an overview of the test locations.

Table 3: Overview of the probe tests

<table>
<thead>
<tr>
<th>Plant</th>
<th>Location</th>
<th>Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>WWTP Morgental, Switzerland</td>
<td>Effluent of primary clarifier</td>
<td>NH\textsubscript{4}-N [mg/l]</td>
</tr>
<tr>
<td>Pilot plant Vienna, Austria</td>
<td>Activated sludge tank</td>
<td>NH\textsubscript{4}-N, NO\textsubscript{3}-N [mg/l]</td>
</tr>
<tr>
<td>Biofilter pilot plant, Austria</td>
<td>Influent of biofilter for nitrification</td>
<td>NH\textsubscript{4}-N, NO\textsubscript{3}-N [mg/l]</td>
</tr>
</tbody>
</table>

**PROBE LOCATION: EFFLUENT OF PRIMARY CLARIFIER**

The new probe was tested at the Morgental WWTP in Switzerland, which is a single-stage activated sludge plant (42’000 p.e.). It treats the digester supernatant from this plant as well as from another plant nearby. The supernatant is collected in a storage tank and then dosed into the primary clarifier inlet. Initially the supernatant could not be added in an optimal way due to the rather high capacity of the supernatant pumps, which regularly lead to peak ammonium loads at the plant (Figure 2). The sensor was located in the primary clarifier effluent channel. No problems due to probe fouling or clogging were observed during the tests.

![NH\textsubscript{4}-N measurement campaign, probe location = primary clarifier effluent channel. Reference measurement: laboratory analysis of 2h-composite samples. Measurement campaign July 2000](image)

Figure 2 shows a comparison of the on-line measurements with results from 2h-composite samples. The 2h samples were collected by means of an automatic timer-controlled sampler with a sampling interval of eight minutes and analyzed by means of flow injection analysis (FIA). Only small deviations were found between the results of the on-line measurement and the laboratory analysis. The 8-minute sampling interval meant that these ammonium peaks were not entirely captured by the 2h-composite samples. The results of the laboratory analysis are consequently significantly lower than the on-line measurements. In view of the uncertainty associated with composite sampling, however, the overall correlation can be regarded as very good.

A second measurement campaign was carried out at the Morgental WWTP in November/December 2000. The sensor was located in the primary clarifier effluent channel. Figure 3 shows the results from the measurement and Figure 4 the correlation between the on-line signal and the laboratory measurements obtained by flow injection analysis. A cyclic dosage of the digester supernatant avoided any capture problems so that an even better correlation could be achieved.
Figure 3: NH₄-N measurement campaign, probe location = primary clarifier effluent channel. Reference measurement: laboratory analysis of 2h-composite samples. Measurement campaign Nov./Dec. 2000

PROBE LOCATION: ACTIVATED SLUDGE TANK

The new probe was tested for a period of five weeks in the second-stage aeration tank of a two-stage activated sludge pilot plant. Details on this pilot plant can be found in Mueller-Rechberger et al. (2000). The ammonium measurement was calibrated twice (Oct. 26 and Nov. 1, see Figure 5), as the first calibration was performed during a period of sharp increase in the ammonium concentration, which resulted in an excessively low calibration offset value. The nitrate measurement was calibrated only once (Oct. 26). The sensor was never cleaned manually; the cleaning interval of the automatic cleaning device was set to four hours. The primary clarifier effluent was fed into the aeration tank of the second stage – which led to the development of a very sticky sludge and severely impaired the operation of a number of other sensors installed at the pilot plant. However, no problems due to insufficient cleaning were observed. Figure 5 shows the NH₄-N concentration in the last cascade of the tank during the test period.
Between the first (Oct. 26) and second (Nov. 1) calibrations, the signal from the in-situ probe was too low due to the insufficient calibration offset value. After the second calibration, the two on-line signals fitted quite well. From Nov. 7 – Nov. 13 the nitrification failed, resulting in NH$_4$-N concentrations above the upper measurement limits of the in-situ probe and the reference analyzer, which were set to 20 mg/l. On Nov. 14, the feeding pump of the pilot plant did not operate for a few hours, thus causing a significant drop in concentration. On Nov. 18, the reference electrode of the in-situ probe suffered problems which resulted in an intermediate rise of the ammonia signal and a synchronous drop of the nitrate signal (see Figure 7). On Nov. 21, the auto-calibration of the reference analyzer failed, resulting in a constant analyzer output signal for a few hours. When the analyzer was put back into operation, its output signal dropped by 2 mg/l for the remaining period of the test campaign. The signal from the in-situ probe and the reference analyzer then ran parallel. All results of the laboratory analysis showed a good fit to the continuous measurement signals.

Figure 6 shows the very good correlation of the signals from the in-situ probe and the reference analyzer. Periods during which the ammonia concentration in the aeration tank exceeded the upper measurement limit are excluded, as are periods in which obvious malfunctions of any of the instruments were observed.

Figure 7 shows the course of the measurement signals of the in-situ NO$_3$-N probe and the reference system, a UV photometer with ultrafiltration. A very good fit was achieved with only a single calibration of the in-situ probe at the start of the test period. Between Nov. 6 and Nov. 14, the two signals diverge, and the probe outputs higher values. During this period, the probe showed a zero-point offset, which may be due to the single-point calibration at the beginning of the test period. No zero-point adjustment was performed. As already mentioned, a malfunction of
the reference electrode of the in-situ probe on Nov. 18 caused a drop in the measurement signal. From Nov. 24 to Nov. 25, the UV photometer output higher values. Since it had been out of operation before that period, the calibration parameters may not have been set correctly at the restart.

Figure 7: NO$_3$-N measurement campaign, probe location = aeration tank. Reference signal = UV photometer with ultrafiltration. Results from laboratory analysis: AT = filtered (paper filter) mixed liquor grab samples, UF = ultrafiltration permeate grab sample

Figure 8 shows the correlation function of the nitrate measurement test in the activated sludge tank. A good correlation was again achieved. It can be clearly seen that the sensitivity of the UV photometer is approximately 0.2 mg/l, since the output signal shows distinct steps of this width. This can also be seen from the graduated shape of the UV photometer signal in Figure 7. Periods during which obvious malfunctions of any of the instruments were observed are not included in the correlation function.

Figure 8: Correlation between the measurement signal from the UV analyzer with ultrafiltration and the in-situ NO$_3$-N probe, probe location: activated sludge tank. Results from laboratory analysis: triangles = filtered (paper filter) mixed liquor grab samples, squares = ultrafiltration permeate grab sample
**PROBE LOCATION: NITRIFYING BIOFILTER INFLUENT**

A final test of the new in-situ probe was carried out in the influent of a biofilter pilot plant. The reference system for the NO$_3$-N measurement shown in Figure 9 was an in-situ single-frequency UV spectrometer.

![Figure 9: NO$_3$-N measurement campaign, probe location = nitrifying biofilter influent. Reference signal = in-situ single-frequency UV spectrometer. LabTest = grab sample](image)

A satisfactory fit between the signal of the nitrate-selective electrode and the UV probe can be observed in this test. The two signals show a divergence from May 7. Although a grab sample was taken on that date, it was impossible to determine which probe was correct due to the sharp drop in concentration. After May 8, the two signals diverge by less than 0.5 mg/l. This divergence may be caused by insufficient calibration as a result of the one-point calibration method at low NO$_3$-N concentrations (c$_{NO3-N}$<1 mg/l). However, it can be regarded as insignificant with respect to the control of an activated sludge process.

Some problems were observed at this test site for the in-situ NH$_4$-N probe. Since no tap water supply was available for probe cleaning, the auto-cleaning device was supplied with biofilter effluent water. This leads to clogging of the water nozzles, which sometimes resulted in probe failures due to sensor fouling. Drifts of the probe signal were observed, which may be due to changes in the wastewater composition. Parallel measurements of the wastewater conductivity showed daily variations of up to 100%.

**CONCLUSIONS**

A new probe for continuous measurement of ammonium and nitrate was successfully applied at a number of different sample locations in Switzerland and Austria. It does not require sample preparation and is installed directly in the process liquid. It showed a good correlation with reference measurements and was operated with almost no maintenance. Since the sensor function is based on potentiometry, any turbidity or colour of the liquid to be analyzed does not interfere with the measurement, which is an advantage over photometric analyzers. Various observations of sensor stability were made during the tests. The new probe operated correctly in the effluent of a primary clarifier with only a single calibration at the beginning of each of the two measurement campaigns. The application in the activated sludge tank required only a single calibration for a test period of five weeks. Some problems with sensor drift were observed during the test at the biofilter pilot plant. These could be explained by substantial changes in the wastewater composition. The automatic cleaning system proved to work correctly, and no problems due to probe fouling occurred even if the probe was located in the effluent channel of a
Suitable Ammonia Sensors

primary clarifier. The new probe can thus be applied at locations which are regarded as difficult to operate with conventional analyzers. This enables the application of advanced control concepts such as feed-forward control. The new probe shows almost no measurement delay, which is also advantageous for plant control. It significantly reduces the investment (by approx. 85 %) and operating cost (by approx. 95 %) for on-line ammonium and nitrate analysis. This makes it possible - even at small plants - to establish extended control strategies such as aeration control on the basis of ammonium measurements for optimizing the energy use and nitrogen elimination.

REFERENCES


CHAPTER 2

COMPUTER AIDED MONITORING AND OPERATION OF CONTINUOUS MEASURING DEVICES

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Computer Aided Monitoring and Operation of Continuous Measuring Devices

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ABSTRACT

Extended studies of measuring and control systems in activated sludge plants at EAWAG revealed that the measuring devices remain the weakest point in control applications. To overcome this problem, a software package was developed which analyses and evaluates the residuals between a reference measurement and the sensor and collects the information in a database. The underlying monitoring concept is based on a two-step evaluation of the residuals by means of statistical evaluations using control charts with two different sets of criteria. The first step is a warning phase in which hints on probable errors trigger an increase in the monitoring frequency. In the second step, the alarm phase, the error hypothesis has to be validated and should allow immediate and targeted reactions from the operator. This procedure enables an optimized and flexible monitoring effort combined with an increased probability of early detection of systematic measuring errors. Beside the monitoring concept, information about the measuring device, the performed servicing actions and the responsibilities is stored. Statistical values for the quantitative characterization of the measuring system during operation will be given. They are needed to parameterise controllers or to guarantee the accuracy of the instrument in order to allow reliable calculations of effluent tax. In contrast to other concepts, not only is the measuring device examined under standard conditions, but so is the entire measuring chain from the liquid to be analysed to the value stored in the database of the supervisory system. The knowledge of the response time of the measuring system is then required in order to allow a comparison of the corresponding values.

KEYWORDS

Monitoring, on-line analyser, control, characterization of measuring devices, trueness, precision

INTRODUCTION

Continuously measuring sensors are not simply enhanced lab instruments: they need adapted servicing and in most cases a well-coordinated monitoring concept with clear decision-support rules. This paper will try to determine how a continuously measuring analyser or sensor can be monitored and characterized under field measuring conditions, and what additional information may be necessary.

Most monitoring concepts for on-line devices in WWTPs commonly used today are based on comparisons of grab samples with a reference method (Häck et al., 1999, ATV 2000) and are applied on a more or less regular basis. In most cases, the criteria are simple boundary conditions, i.e. the differences have to be located within a defined range. This provides an isolated snapshot of the situation, whereas concepts based on a dynamic view using time-series information will be much more efficient and reliable in detecting a bias. A drift effect, for example, can be identified not only by the error boundaries but much earlier by using time-series
information. The operator’s dilemma is that he wishes to have a high probability of detecting a bias while minimizing his measuring effort.

The quantitative characterization of measuring systems during operation is still an open question. In our opinion, there is a need for clear and comparable values which should be understandable to the plant staff as well as to specialists. Sophisticated statistical calculations are then excluded. If they are needed, however, they must be translated into linguistic variables which provide clear and easily understandable decision support. A Knowledge of the trueness, precision and response time of the measuring system is of major interest for control applications (Rieger et al., 2003). The first two points can be calculated from the residuals between the reactor concentration measured with grab samples and the on-line device values used in the SCADA (Supervisory Control And Data Acquisition) system, the latter has to be evaluated before a monitoring concept starts.

In addition to the monitoring task, various information is necessary to run the measuring device at an optimum. Beside the statistical and graphical evaluation of the monitoring data, an analysing tool should provide information about the servicing actions. This allows effective error diagnosis and an estimation of the time and costs required for servicing actions. The responsibilities and information concerning the manufacturer and supplier should also be available in the analysing tool.

If the requirements described above are implemented in a software environment, the efficiency of the data analysis is enhanced and the availability of information for the plant operators is increased. The proposed software package is based on an access database and an analysing and evaluation tool under Matlab/Simulink. This non-commercial package can collect and utilize all necessary and relevant data about the observed measuring device.

**GEKO – A MONITORING SOFTWARE**

Our studies indicate that the measurement is still the weakest point in the control chain. Without a good monitoring concept, a control application will never give the best possible and sustainable results. The software developed (GEKO = GEräteKontrolle) is designed to satisfy the following requests:

- **An efficient monitoring concept** which helps to minimize the effort required for comparative measurements and to enhance protection against systematic measuring errors (drift, shift and gross errors as well as insufficient calibration). It includes decision-support rules for the plant staff.
- **Characterization of the measuring device** (response time, precision, trueness)
- **Documentation**
  - Storage of all measurements (reference and the corresponding device values), statistical calculations, the name of the person who took the measurements as well as all servicing actions and calculations of the average time requirement for the device [h/week]
  - Definition of responsibilities
  - Device description and information about the manufacturer/supplier

**A MONITORING CONCEPT FOR MEASURING DEVICES**

The proposed concept (Thomann et al., 2002; Rieger et al., 2001) is based on the analysis of reference measurements (normally from the lab) and the corresponding values of the measuring device from the SCADA system taking into account the response time. It deals with two different monitoring levels: the first level is a warning phase in which possible errors are detected. It triggers a servicing action and an increase in the monitoring effort (normally a repeated
Monitoring of On-line Sensors

measurement the next day). The second level or alarm phase indicates an out-of-control situation and triggers a change to manual control or less sophisticated strategies. Figure 1 shows the monitoring concept according to Thomann et al. (2002) and Figure 2 lists the used criteria. Western Electric rules (Montgomery, 1996) are applied at the alarm level as criteria for the control chart, whereas more stringent criteria are used for the warning level. The required warning and alarm limits have to be derived from preliminary measurements and are defined as two and three standard deviations respectively. For more information, see Thomann et al. (2002). The proposed monitoring concept is based on a standard measuring interval (normally five days) which is increased if a warning occurs. As a result, the monitoring effort is low during in-control phases and maximized if a warning is shown.

The concept can be applied to all measuring devices if a reliable reference method is available. Examples are on-line analysers and sensors (reference: lab measurements), level measurements (reference: point gauge), laboratory photometers (reference: standard solutions and recovery experiments), balances (reference: standard weights), etc.

Figure 1: Monitoring concept for measuring devices (Thomann et al., 2002). The bold arrow cycle shows the sequence of actions performed if the measuring process is assumed to be in-control.
**Monitoring of On-line Sensors**

**Warning Phase**
- a) 1 point outside of the warning limits
- b) 4 consecutive points on one side of the center line
- c) 4 points in a row steadily increasing or decreasing

**Alarm Phase**
- a) 1 point outside of the control limits
- b) 2 of 3 consecutive points outside the warning limits but still inside the control limits
- c) 8 consecutive points on one side of the center line
- d) 6 points in a row steadily increasing or decreasing

**Characterization of Measuring Systems During Operation**

The monitoring concept can detect systematic errors. It cannot detect random errors unless a value is beyond the warning or alarm limit. However, the limits should then be recalculated. The GEKO software therefore calculates values to quantify the accuracy of the measuring system within in-control periods. Knowledge of the precision can be used to parameterise controllers more effectively, for instance. The response time must be checked in advance because the reactor concentration must be compared with the corresponding value of the measuring system and is also one of the key parameters for controller design (Rieger *et al.*, 2003).

**Response Time**

The observation of measuring devices as well as control applications requires the knowledge of the response time not only of the analyser but also of the entire measuring system including sample preparation, where this exists. The response time or $T_{90}$ is defined in an ISO standard (ISO 15839, 2003). A study at EAWAG covered various methods for detecting the response time of the entire measuring system depending on the type of analyser.

**Uncertainty**

No systematic errors (bias or trueness) are allowed if the effluent concentration is being monitored e.g. to calculate an effluent quality tax. For control applications, knowledge of the precision is most important. Both parts of the uncertainty – trueness and precision – should be calculated from measurements during operation and for the complete measuring chain from the measuring site to the SCADA system (taking into account the response time). No values based on repeated measurements of the same sample can therefore be calculated (e.g. precision from repeatability experiments).

In the proposed concept, trueness and precision will be differentiated on the basis of the linear regression of the device values versus the monitoring data. The trueness is given as the resulting slope ($\beta$) and offset ($\alpha$) if the deviation of $\beta$ and $\alpha$ from 1 and 0 respectively is significant on a 5% significance level using a $t$-test (Draper and Smith, 1981). The precision is then given as a 95% prediction interval (or confidence interval for a predicted value) based on the linear regression. If no significant bias (at a 95% significance level) is detected, it is proposed to use only the 95% prediction interval based on the assumption of ideal calibration ($\beta = 1, \alpha = 0$). This
Monitoring of On-line Sensors

Monitoring of On-line Sensors will include the uncertainty of the complete measuring chain in one interval. The complete characterization concept with a detailed description and the necessary equations is given in Rieger et al. (submitted).

The calculated uncertainties contain all random and systematic deviations due to device and lab errors, signal transmission, sampling etc. To differentiate between the sources an error propagation must be calculated. For more information, see Thomann (2003).

DOCUMENTATION AND GRAPHICAL EVALUATION

All relevant data from the comparative measurements to the servicing actions will be stored and documented in a MS-ACCESS database, which guarantees a simple data exchange with other programs. It can then be used to derive the weekly effort required for the examined device or to carry out an effective error diagnosis, e.g. to identify the cause of a shift in the time series. Beside the database and the statistical calculations, the monitoring software places special emphasis on diagrams in order to allow fast graphical evaluation of the instrument and quick hints on possible errors. Figure 2 shows all the residuals and servicing actions (vertical lines, description on mouse click) of the device described in the case study.

CASE-STUDY

A phosphate analyser (Stamolys CA 70 PH, Staiger-Mohilo, now Endress+Hauser Metso AG, Reinach, Switzerland, molybdate-vanadate method) was tested. It was used for monitoring the effluent quality at an EAWAG membrane pilot plant at WWTP Kloten-Opfikon (Switzerland). The pilot plant treats the wastewater of ca. 100 p.e. and is designed to compare three different membrane modules and reduce micropollutants by means of membrane bioreactors (MBR) (Joss et al., 2004). No probe filtration was necessary since the pre-filtered effluent of the MBR was
Monitoring of On-line Sensors

used. The comparative measurements were performed in the plant laboratory using test kits from Dr. Lange (LCK349/350).

**Preliminary Tests**

In a first phase, the analyser was installed and some basic checks - such as repeated measurements of standard solutions and recovery experiments – were carried out in order to obtain a basic calibration and to define the warning and alarm limits of the control chart (Figure 1). The test showed an extremely high variation of the results. The observation of the calibration factor (Figure 3), which is set after the auto-calibration procedure, gave a hint as to the source of error. In an evaluation of the measuring chain it became clear that the recipe of the lab-made molybdate reagent (given by the supplier) was wrong, resulting in a slow chemical reaction (Figure 4). Change-over to reagents delivered by the device supplier and implementation of a new calibration curve led to the calibration factors scattering in an acceptable range. A new test with lab-made reagents using a new recipe again yielded fluctuating calibration factors. After these experiences only original reagent powder from the supplier was used. It should be mentioned that a chemical from Hach (via Dr. Bruno Lange GmbH & Co. KG, Düsseldorf, Germany) was supplied instead of the original from the manufacturer, but this seems not to have given the analyser any problems.

For the definition of the response time ($T_{90}$), it was checked whether the concentration measured within an interval of 15 min is stable and reflects the concentration of the specified standards. The results confirmed that the measuring interval is long enough to completely substitute the solution in the tubes and the analyser. The warning and alarm limits for the control-chart concept were set to 0.4 and 0.6 mg/l respectively on the basis of repeated measurements of standards and wastewater samples.

![Figure 3: Calibration factors of the PO₄-P analyser during operation](image)

![Figure 4: Experiment in order to evaluate the reaction time using two different reagents (at 1.96 mg P/l)](image)
MONITORING CONCEPT

After these preliminary tests and a basic calibration, the monitoring concept was applied by means of the GEKO software package. Figure 5 shows the residuals (analyser – lab values), which were measured between Nov. 28, 2002 and Aug. 5, 2003. In the period between Jan. 6 and Feb. 10, the tests were carried out with the second recipe and only the calibration factor was observed by measuring standard solutions. Consequently, this period is only shown but is not used for the comparison between real and adapted data.

Further systematically lower measurements lead to the identification of an unsuitable ascorbic acid reagent causing incomplete reaction (Figure 5). Since March 11, 2003, ascorbic acid reagent was made by the EAWAG lab using original chemicals delivered by the supplier. Problems arose due to instabilities of the reagents over time. Tests using EAWAG’s own nano-pure water for the solution did not yield any better results. Special emphasis should consequently be given to the age of the chemicals. Since May 14, 2003, the analyser has been operating more or less reliably. The trueness was further improved with a new calibration curve (June 6) based on measured standard solutions. On June 27, the calibration curve was adapted slightly in order to take the water matrix into account. Since then, the analyser has operated with high accuracy and without significant problems.

In this case study, we did not take full advantage of the flexible monitoring concept. To give an impression of how this concept can shorten the time needed to detect errors and increase the monitoring intervals, the concept is applied to real data with a normal in-control (without a warning) measuring interval of five days. It is normal to have at least one measurement per week on different days, as proposed by the German ATV (ATV 2000). After a warning, the interval is reduced to one day according to our monitoring concept. Figure 5 (bottom) shows the real data but with the optimized monitoring effort. Looking at the interval between the start of monitoring (here Feb. 10, 2003) to the time when the analyser gives reliable results (Figure 5 top: June 27 with real data, bottom: April 25 with the flexible concept) it can be clearly seen that the...
application of this concept improves the availability of the measuring device. The flexible concept increases the availability of the device by a factor of 1.6. A possible restriction is that drift effects will be smaller with the flexible concept so that the two warnings will not occur due to an overlap of the warning limits. For the analyser described, the monitoring effort was extremely high, with twice-daily measurements on some occasions. The monitoring effort in currently used concepts is set to once per week. Use of a boundary condition of, say, 0.2 mg/l, would greatly increase the time needed to detect the source of error, since only few residuals are outside the limit. The time-optimized control strategy supported by GEKO uses the time-series information and therefore detects systematic errors much earlier.

**Characterization of the Measuring Device**

The in-control period since June 27 was used to characterize the measuring device during operation. The trueness can be stated as the result of a linear regression (ISO 8466-1, 1990) with parameters for slope and offset. Tests of linearity and the relationship between the sensor and the reference method have to be performed to check for any significant hints on systematic calibration problems and whether the data available are suitable for the regression.

For the analyser under evaluation, the slope $\beta$ is 0.996 and the offset $\alpha$ equals $-0.01$ mg P/l. The deviation of $\beta$ and $\alpha$ from 1 and 0 is not significant on a 5% significance level and the accuracy is thus stated only as a precision giving a 95% prediction interval for future measurements (Rieger et al. submitted). Figure 6 shows a very good correspondence between lab and analyser values. The width of the 95% confidence interval for the ideal calibration curve ($\beta = 1$, $\alpha = 0$) is very narrow with 0.05 mg P/l at a mean value of 1.71 mg P/l. The interval contains all possible calibration curves with a probability of 95%. This means that the ideal calibration fits well with the data. The 95% prediction interval (also known as the 95% confidence interval of a predicted value) is 0.16 mg P/l at a mean lab value of 1.71 mg P/l. A future value should be in this interval with a probability of 95%.
CONCLUSION

Use of the proposed concepts embedded in a software package allows the plant staff to operate their measuring equipment in an optimal way. The concept permits early detection of drift, shift and outliers as well as poor calibration of the sensor. Since the two-step control chart uses two different criteria, an increased control frequency will only be required if a warning situation is detected. This results in an optimized measuring effort.

In the authors’ opinion, the proposed concepts and documentation will greatly increase the accuracy, reliability and acceptance of the measuring device. The knowledge of the trueness and precision of the devices under field conditions will be made available to the plant operators and specialists. On the basis of this information, control strategies can be better adapted to the processes and more sophisticated control concepts will be possible.

The knowledge of the trueness increases the reliability of dynamic process monitoring. This concept allows the continuously measuring sensors to be used for self surveillance (WWTPs in Switzerland, Germany and Austria are monitored with a combination of control measurements carried out by the authorities and a monitoring program run by the plant staff) instead of laborious lab measurements. The benefits of this method include an effluent tax which reflects the overall situation more faithfully thanks to the availability of dynamic data. However, this is still a future scenario, since on-line devices are currently not allowed in the surveillance regulations. The concept proposed here can help to define guidelines for the required accuracy and increase the reliability and therefore the acceptance of continuous measuring devices.

GEKO also provides valuable information for future design and optimization studies. Dynamic simulation studies in particular have to rely on accurate continuously measured data (Langer-graber et al., 2004). It also helps to assess the profitability of complex control concepts.

A critical point occurring during the tests on WWTPs was the implementation of the flexible monitoring concept in the daily routine of the plant staff. A next step should be to include the GEKO software in the plant database in order to automate read-out of the on-line data and therefore make its use easier and faster for the staff. The goal is to have an independent stand-alone package which has enough interfaces to connect to different databases, GEKO is currently a non-commercial software package, but it is planned to further develop the concept in cooperation with a software company.

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CHAPTER 3

QUANTIFYING THE UNCERTAINTY OF ON-LINE SENSORS AT WWTPS DURING FIELD OPERATION

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Quantifying the Uncertainty of On-line Sensors at WWTPs during Field Operation

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ABSTRACT

It remains an ongoing task to quantify the uncertainty of continuous measuring systems at WWTPs during field operation. The commonly used methods are based on lab experiments under standardized conditions and are only suitable for characterizing the measuring device itself. For measuring devices under field conditions, a knowledge of the response time, trueness and precision is equally important.

A method is proposed which can be used to characterize newly installed on-line sensors or to evaluate monitoring data which may contain systematic errors. The concept is based on comparative measurements between the sensor and a reference. A linear regression is used to differentiate between trueness and precision. Various statistical tests are conducted to validate the preconditions of linear regression. The information about the trueness and precision of the measuring system under field conditions helps to adapt control strategies more effectively to the relevant processes and permits sophisticated control concepts. Moreover, the concept can help to define guidelines for evaluating the uncertainties of effluent quality monitoring.

The approach is discussed in detail in this paper and all statistical tests and formulas are listed in the appendix.

KEYWORDS

Uncertainty, response time, on-line sensor, monitoring, trueness, precision.

NOMENCLATURE

\[\alpha = \text{Estimated intercept of regression function}\]
\[\beta = \text{Estimated slope of regression function}\]
Accuracy = The closeness of agreement between a test result and the accepted reference value (ISO 5725-1, qualitative term)
Bias = Total systematic error (quantitative term)
\[f = \text{Degrees of freedom}\]
\[F(\nu_1, \nu_2, 0.99) = \text{F-distribution at 1% significance level}\]
\[n = \text{Number of measurements}\]
PG = Test statistic
Precision = Term for random errors: The measure of precision is usually expressed in terms of imprecision.
Prediction interval = Confidence interval for a predicted value
\[s_y = \text{Residual standard deviation}\]
\[se_\beta = \text{Standard error of } \beta\]
\[se_\alpha = \text{Standard error of } \alpha\]
\[t(\nu, 0.95) = \text{t-distribution at a 5% significance level}\]
Trueness = Term for systematic errors: the closeness of agreement between a measurement and an accepted reference value. The measure of trueness is usually expressed in terms of bias.
Uncertainty = Precision + trueness
Variability = In the present case, measuring deviations due to changing matrices
\[x_i = \text{Conc. of the } i\text{th reference sample (from lab)}\]
\[\bar{x} = \text{Average over } x_i\]
\[y_i = \text{Conc. of the } i\text{th value of the measuring device}\]
\[\bar{y} = \text{Average over } y_i\]
\[\hat{y}_i = \text{Estimated measuring device value corresponding to } x_i, \text{predicted from a regression function}\]
\[y_0 = \text{Control variable for calculating the intervals}\]
INTRODUCTION
Depending on the goal of the measurement setup, different sources of uncertainty are relevant. When monitoring the effluent concentration - e.g. in order to calculate an effluent quality tax - no systematic error (deviation from trueness) is allowed. For control applications on the other hand, a knowledge of the random error (precision) and the ‘error’ caused by the response time are most important (Rieger et al., 2003).

To evaluate the uncertainty of an on-line sensor during field operation, an approach is needed which reflects the specific measuring chain and is applicable to WWTPs. Various approaches are described in the literature for detecting, locating or even quantifying the uncertainties of measuring devices. The following list is incomplete but gives a sufficient impression of the main directions:

- Estimated total uncertainty (ISO, 1993): A theoretical approach in which the total error is calculated on the basis of the potential uncertainty of the individual sources of error using an error propagation approach. The total uncertainty of the measuring chain is expressed as a confidence interval.
- Comparison with a reference method (e.g. ISO 15839, 2003): The device under evaluation is compared with a reference measurement or a standard solution. The precision is usually tested with repeated measurements at the same concentration.
- Mass balances (Thomann, 2003; Meijer et al., 2002; Nowak et al., 1999): Mass balances using redundant information with overlapping boundaries for several fluxes of wastewater, sludge or gas compounds as well as energy flow are used to locate and quantify measuring errors.
- Stochastic evaluation of typical / untypical states (Rosen and Lennox, 2001; Yoo et al., 2004): Stochastic approaches (e.g. with principal component analysis PCA or independent component analysis ICA) allow any deviations of the measuring signal from normal conditions to be detected.

The advantage of a stochastic evaluation is that each measuring value is evaluated, whereas the other methods are off-line evaluations. A disadvantage is that only significant deviations from a defined state are detected and no absolute values of the uncertainty can be given. Mass balances give information about the trueness of several measurements of concentrations and flows, but tell us nothing about the precision of a single instrument. The total uncertainty concept differentiates the sources of the errors. This is very interesting for specialists but is not usually required for regular plant operation. We selected the second approach of taking independent measurements but had to make some adaptations in order to apply these methods to on-line sensors during field operation.

Most specifications for measuring devices are based on repeated measurements of standard solutions under standard conditions (ISO 15839, 2003; ISO 5725-1, 1994; ISO 8466-1, 1990). This is important and is suitable for characterizing the measuring method or comparing different devices. In contrast, the goal of this work is to define procedures for characterizing the entire measuring chain during field operation.

In our concept, both parts of the uncertainty, namely trueness and precision (Figure 1), will be calculated from comparative measurements during operation and for the complete measuring chain from the measuring site to the SCADA (Supervisory Control and Data Acquisition) system (taking into account the response time). A problem is that the commonly cited precision under conditions of repeatability (e.g. ISO 15839, 2003) is only valid for the same water matrix by definition, whereas the values obtained during field operation include the variability caused by different matrices as well as the effects of random and systematic measuring errors. For this reason, the main task is to find a method which differentiates between precision and trueness.
Since no differentiation between the matrices is possible, the variability will be included in the precision.

Figure 1: Definition of systematic errors (trueness) and random errors (precision)

CHARACTERIZATION METHOD

The characterization method can be applied to two different cases:
- Characterization of newly installed on-line sensors (e.g. for a comparison of sensors).
- Evaluation of monitoring data which may contain systematic errors.

The first approach allows the trueness and precision of new instruments to be investigated and is intended mainly for plant operators. The second case takes the common situation into account that monitoring data exist, but no check on systematic errors had been carried out during the measurements. The main users will be engineers who have to evaluate the data quality of the sensors.

The calculated uncertainties of the comparative measurements contain all random and systematic deviations (Figure 1) of the measuring chain due to the variability of the matrices, device and lab errors, signal transmission, sampling etc. Since the concept is designed for practical use at WWTPs, it must be as simple as possible. The goal of our approach is to differentiate between trueness and precision on the basis of a linear regression. Differentiation between the sources of errors is not discussed in the present paper.

The authors propose to calculate the uncertainty of the measuring device by the approach described in Figure 2. After some preliminary checks, mainly of the accuracy of the reference measurements and the determination of the response time, various statistical tests are carried out in order to guarantee the applicability of the linear regression. In the basic part of the concept, a decision has to be made as to whether it is necessary to differentiate between trueness and precision (Figure 1). If the measuring chain works according to the manufacturer’s specifications, there should be no significant bias and all uncertainty (including any possibly remaining bias) is included in the precision. If a bias (systematic error) is detected, a linear regression (see eq. 1) is used to differentiate between trueness and precision.

ASSUMPTIONS

The following assumptions are made:
- Bias-free reference – reference measurements in the lab are free of errors.
  (If the precision of the reference method is known, a more complex regression method can be used which takes the uncertainty of the reference measurements into account; see Bertrand-Krajewski, 2004, for example).
- Normality - the random errors should be normally distributed at each level of concentration.
- Independence - the random errors associated with one observation are not correlated with those of any other observation.
**Preliminary Checks**

**Accuracy of reference:** The reference measurements in the lab must be free of bias. This should be achieved with the aid of the following experiments (Thomann, 2003):

- Analysis of the calibration characteristics with standard solutions (ISO 8466-1, 1990)
- Recovery experiments (or standard addition experiments) on the matrix for the analysis of potential interferences (Funk et al., 1992)
- Dilution experiments with the matrix to analyse sum parameters (e.g. COD) or total components (e.g. N_{tot}, P_{tot}) where the decomposition is the crucial part of the analysis and recovery experiments would only test the decomposition of the standard solution
- Comparison of the investigated with alternative standard method (e.g. APHA, 1995)

**Response time:** To compare measurements from a continuously measuring device with a reference measurement (from the laboratory), it is essential to know the exact response time not only of the analyser but also of the entire measuring system including sample preparation.

---

**Figure 2:** Approach of the characterization concept

**Figure 3:** Definition of response time (ISO 15839, 2003): Response to a concentration step change
The response time (Figure 3) is the time interval between the instant when an on-line analysing system is subjected to an abrupt change of the influent concentration and the instant when the readings cross the limits of (and remain inside) a band defined by 90% and 110% of the difference between the initial and final values of the abrupt change (ISO 15839, 2003).

**Tests to Validate the Applicability of the Linear Regression**

In the following section, some general problems of the linear regression are discussed and some tests proposed to validate its applicability.

**Linear regression:** For the following calculations, a linear regression model (eq. 1) is used which will be fitted with the least squares method. It should be kept in mind that in contrast to ISO 8466-1 (1990), the goal of the linear regression is not to derive a calibration function but to calculate the trueness based on two independent measurements of the same sample.

\[ y_i = \beta \cdot x_i + \alpha + \varepsilon_i \]

where \( \beta = \) slope, \( \alpha = \) offset, \( \varepsilon_i = \) random error \( (\varepsilon_i \sim N(0, \sigma^2)) \)

\( y_i = \beta \cdot x_i + \alpha + \varepsilon_i\)

where \( \beta = \) slope, \( \alpha = \) offset, \( \varepsilon_i = \) random error \( (\varepsilon_i \sim N(0, \sigma^2)) \) (1)

*Figure 4: Typical scenarios for linear regression*

Figure 4 shows different scenarios of a regression analysis. General problems exist if no significant correlation results or if a single or few observations cause a large difference between the two independent measuring methods:

- **Closely scattered points:** The data points are concentrated in one region. No significant correlation can be calculated (Figure 4B).

- **Leverage points:** An observation with an extreme value on a predictor variable is called a point with high leverage. Leverage is a measure of how far an independent variable deviates from its mean. These leverage points can have an unusually large effect on the estimate of regression coefficients (Figure 4C).

- **Outliers:** An outlier is an observation with a large residual. In other words, one whose dependent variable value is unusual given its values on the predictor variables. An outlier may indicate a sample peculiarity, a data entry error or other problems (Figure 4D and E).

- **Non-linear correlation:** The data points cannot be fitted with a straight line (Figure 4F).

In our concept, this will be evaluated with a linearity test.

**Number of comparative measurements:** At least ten data points (ISO 8466-1, 1990) are recommended for a linear regression. At least twenty measurements should be available for testing the homogeneity of the variances.
Relationship between sensor and reference measurement: In order to evaluate the general relationship between the value of the measuring device and the reference measurement, the coefficient of correlation \( r^2 \) is often used. A better method to deal with the general problems of a regression analysis (Figure 4A, B, C) is to test the null hypothesis \( H_0: \beta = 0 \) (slope = 0 means that the distribution of \( y_i \) is equal for all \( i \) independent of the \( x_i \) value) against the alternative hypothesis \( H_A: \beta \neq 0 \) (i.e. there is a correlation).

Outlier elimination: The data pair with the highest absolute residual between the regression function and the measured sensor value is taken as a potential outlier (Figure 4D and E). An F-test is used to evaluate whether the residual standard deviation \( s_y \) (eq. 11) is significantly reduced after elimination of this outlier (eqs. 7 and 8). The number of eliminated outliers must be less than 10% of the total number of measured values.

Working range/measuring range: To describe a measuring device, its measuring range is normally given (ISO 15839, 2003). Since the available measurements are not always distributed equally over the whole range, this would lead to an inadmissible extrapolation. Our concept uses the working range, which is covered by comparative measurements (Figure 7).

Linearity: In order to check the linearity between sensor and reference measurements (Figure 4F), an F-test (eq. 10) evaluates whether a quadratic regression function (eq. 9) fits the data better than a linear function (eq. 1). If the quadratic function provides a significantly better fit to the internal calibration function of the device which calculates the concentration on the basis of the raw values, it is unsuitable for the chosen measuring range. So the measuring range must be reduced until a linear regression function is sufficient or else the internal calibration function must be adapted.

Homogeneity of variances: A precondition for an unweighted linear least squares fit is that the variance of the values measured by the measuring device is independent of the concentration (Figure 5). If this precondition is not fulfilled, the least squares fit of the linear regression model may give incorrect results. For the proposed concept, this means that the differentiation between trueness and precision fails, thus leading to the calculation of a lower precision. A more serious problem is that it can cause the detection of a non-existent systematic error or vice versa the non-detection of an existing error.

ISO 8466-1 (1990) proposes ten measurements of the highest and lowest standards to calculate the homogeneity of the variances. Since no repeated measurements of the same sample are available in our data, we propose to use the residual standard deviation \( s_y \) (eq. 11) for the range up to 25% and over 75% of the sorted data (Figure 5D). \( s_y \) is based on a linear regression over all the data.

If a significant inhomogeneity is detected by an F-test (eq. 12), the working range may have to be limited or alternatively a weighted regression will have to be used. Examples of sensors with inhomogeneous variances are colorimetric probes in which the signal can become imprecise with increasing concentration. Another example are ion-sensitive probes whose internal calibration function is logarithmic and can therefore cause a logarithmic increase of the variances to the measured raw values.
Uncertainties of On-line Sensors

**Weighted linear regression:** If the variances are inhomogeneous over the working range (Figure 5B), one solution is to use a weighted linear regression. The appropriate weight is proportional to how well a given $y_i$ is known or inversely proportional to the uncertainty of $y_i$. If the variance of the measurement is proportional to $x_i$ (Figure 5B), this value can be used as a weight for a weighted least squares fit (Baird, 1995; eqs. 13 and 14). Since the variances at the different levels are normally unknown, we propose two solutions:

- Additional experiments with multiple measurements of standard solutions (ISO 15839, 2003) at least at 20% and 80% of the measuring range. If the change in variances is linearly distributed over the measuring range (Figure 5B), the precision at each level can be calculated from the experiments. Otherwise (Figure 5C), the measuring range should be reduced.

- Using the available data with the aid of the residual standard deviation $s_y$ for the range up to 25% and over 75% of the sorted data (Figure 5D). It has to be tested whether the change in the variances is linear. This can be done with the same test on linearity as proposed in eqs. 9 and 10 for a moving average of $s_y$ over five data points. It is an iterative method because the first results are based on a linear unweighted regression. The stop criterion is reached if the homogeneity test using the weighted variances (based on the weighted least squares fit) is satisfied.

**CHECK ON SYSTEMATIC ERRORS**

This test is meant to check whether the sensor measurements contain a systematic error. The 95% confidence interval of the regression function is used to evaluate whether the deviation of the estimated linear regression model (eq. 1) and the ideal relation of $\beta = 1$ and $\alpha = 0$ is significant. The confidence interval (within the working range) has to include the ideal relation in order to guarantee that no significant systematic error exists.

The 95% confidence interval contains all possible regression curves with a probability of 95% (eq. 2). The interval width depends on the number and variance of the data and its distribution within the measuring range. A tight interval means a good correspondence between predictors and the outcome variable. For the graphical representation of the results the ideal relation, the estimated regression function and the 95%-confidence interval of the regression function (CI$_{95\%}$) should be plotted (Figure 6).

$$\text{CI}_{95\%} = (\alpha + x_0 \cdot \beta) \pm t_{(0.975,f=n-2)} \cdot s_y \cdot \sqrt{\frac{1}{n} + \frac{(x_0 - \bar{x})^2}{\sum_{i=1}^{n} (x_i - \bar{x})^2}}$$

where: $t_{(0.975,f=n-2)}$ t-distribution with n-2 degrees of freedom and a significance level of 5%.

- If no significant bias (on a 5% significance level) is detected, we propose to use the 95% prediction interval based on the assumption of an ideal relation ($\beta = 1$, $\alpha = 0$). This will include the uncertainty of the complete measuring chain in one interval.

- In case of a significant bias, the trueness is given as the resulting slope ($\beta$) and offset ($\alpha$). The precision is stated as a 95% prediction interval (or confidence interval for a predicted value) based on the linear regression. This should be the exception and requires a detailed investigation of the measuring chain.
REPRESENTATION OF THE UNCERTAINTIES

Measurements without significant systematic error

Total uncertainty: If no systematic errors were detected, it is sufficient to include all errors in one interval. We propose to use a 95% prediction interval \( \text{CI}_{\text{pred,ideal}, 95\%} \) value based on the assumption of an ideal relation. This means that the value of the measuring device is compared directly with the reference method without previous regression. The normal standard deviation \( s \) is used for the calculation because an ideal relation between sensor and reference value is assumed.

\[
\text{CI}_{\text{pred,ideal}, 95\%} = y_0 \pm t_{(0.975, f = n-2)} \cdot s \cdot \sqrt{1 + \frac{1}{n} + \frac{(y_0 - \bar{y})^2}{n \sum_{i=1}^{n} (x_i - \bar{x})^2}}
\]

where: \( t_{(0.975, f = n-2)} \) t-distribution with n-2 degrees of freedom and a significance level of 5%

Measurements with systematic error

Trueness: The trueness contains all the biases of the measuring chain (e.g. from systematic sampling errors or signal transmission). The trueness should be given in the form of a linear regression equation (eq. 1) with the 95% confidence intervals for \( \beta \) and \( \alpha \).

\[
y_i = \beta (\pm \text{CI}_{95\%}, \beta) \cdot x_i + \alpha (\pm \text{CI}_{95\%}, \alpha)
\]

Precision: The precision includes all random errors of the measuring system (e.g. from sampling, variability or random analytical errors in the lab). It should be given in the form of a 95% prediction interval \( \text{CI}_{\text{pred}, 95\%} \), eq. 3). This interval defines the range of a future single measurement with a probability of 95% (Funk et al., 1985). The calculation is based on the regression function (see trueness) and takes into account random errors of the measuring chain. Since the precision of the sensor value must be predicted, the commonly used equation has to be solved for \( x_0 \). This equation is derived in Funk et al. (1985). The first term describes the inverse regression function.

\[
\text{CI}_{\text{pred}, 95\%} = y_0 - \frac{\alpha}{\beta} \pm t_{(0.975, f = n-2)} \cdot \frac{s_y}{\beta} \cdot \sqrt{1 + \frac{1}{n} + \frac{(y_0 - \bar{y})^2}{\beta^2 \cdot n \sum_{i=1}^{n} (x_i - \bar{x})^2}}
\]

where: \( t_{(0.975, f = n-2)} \) t-distribution with n-2 degrees of freedom and a significance level of 5%

CASE STUDY

To demonstrate our concept, an in-situ spectrometer probe is monitored (spectro::lyser, scan Messtechnik GmbH, Vienna, Austria) which measures the COD\(_{\text{tot}}\) in the effluent of the primary clarifier of WWTP Thunersee, Switzerland. Because an optical probe was used, the response time is a function only of the measuring interval, which is set to 1 per min.

Extensive evaluations were made in order to ensure accurate reference measurements. The statistical tests revealed five outliers but no other significant results with respect to the standard procedure (Table 1). Since no systematic errors were detected, only the 95% prediction interval need be given. The good correlation can also be seen from Figure 6, which shows the 95% confidence interval of the regression function. The interval is very tight and includes the ideal relation \( (\beta = 1, \alpha = 0) \). This means that the deviation is not significant on a 5% significance level.
## Uncertainties of On-line Sensors

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<td>Test on general relationship between sensor and lab values</td>
<td>Signif. relationship between sensor and lab measurements</td>
<td>5</td>
<td>OK</td>
<td>26.878</td>
<td>$t_{0.975, f=n-2}$</td>
</tr>
<tr>
<td>Linear regression</td>
<td>$y_i = 0.947 * x_i + 10.163$</td>
<td>1</td>
<td>OK</td>
<td>26.878</td>
<td>$t_{0.975, f=n-2}$</td>
</tr>
<tr>
<td>Working range</td>
<td>48 – 473 mg COD/l</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Test on linearity</td>
<td>No significant improvement of correlation if non-linear function is used</td>
<td>9,10</td>
<td>OK</td>
<td>-39.752</td>
<td>$F_{0.99, f1=1, f2=n-3}$</td>
</tr>
<tr>
<td>Test on homogeneity of variances</td>
<td>Inhomogeneity not significant</td>
<td>12</td>
<td>OK</td>
<td>1.608</td>
<td>$F_{0.99, f1=10, f2=11}$</td>
</tr>
<tr>
<td>Check on systematic errors</td>
<td>Ideal relation inside CI</td>
<td>2</td>
<td>Total uncertainty (no differentiation between trueness and precision)</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

### Uncertainty

<table>
<thead>
<tr>
<th>Total uncertainty (outliers eliminated)</th>
<th>± 50.7 mg COD/l</th>
</tr>
</thead>
<tbody>
<tr>
<td>(95% prediction interval)</td>
<td>at mean lab value of 207 mg COD/l</td>
</tr>
<tr>
<td>Total uncertainty (all data)</td>
<td>± 74.6 mg COD/l</td>
</tr>
<tr>
<td>(95% prediction interval)</td>
<td>at mean lab value of 212 mg COD/l</td>
</tr>
</tbody>
</table>

**Uncertainty of the regression function**

- 95% confidence interval of the regression function
- Outlier
- Regression function

**Total uncertainty (95% Prediction interval)**

- CODtotal
- Ideal correlation
- 95% prediction interval (based on ideal correlation)
- Outlier

Figure 6: Uncertainty of the regression function (95% confidence interval of the regression function without outliers)

Figure 7: Total uncertainty of the sensor (95% prediction interval for future single measurements without outliers)

Figure 7 shows the total uncertainty with the 95% prediction interval based on an ideal relation. The interval width is ± 50.7 mg COD/l at the mean lab value of 207 mg COD/l. A future single value should be contained within this interval with a probability of 95%. Without the outlier elimination, the prediction interval would be ± 74.6 mg/l at a mean lab value of 212 mg COD/l.

### DISCUSSION

A precondition for the use of the concept presented here is the accuracy of the laboratory measurements. It is clearly possible to include this accuracy in the calculations and distinguish between lab and sensor errors, but this would require a major additional effort to characterize the lab measurements. In our opinion, the lab measurements should be free of bias, whereas the precision can be neglected, at least in the trueness calculations. As a rule, the accuracy of the analytical method used in the plant laboratory is monitored by the relevant authorities. Our
Uncertainties of On-line Sensors

experience has shown that analytical methods are accurate enough, but each individual application in a specific plant laboratory has to be evaluated separately (Thomann, 2003).

A critical point regarding uncertainty is the occurrence of drift effects which cannot be detected due to the lack of time information in the data used. The result is a lower precision.

We had a long discussion as to whether outliers should be eliminated or not. Since the regression can be strongly influenced by outliers, we decided to eliminate them on a 1-% significance level. This would allow the trueness to be calculated without the influence of the most significant outliers. As regards the precision, we think that the outliers should be shown but not included in the calculation. Good practice would be to give the precision with and without the outliers.

If the variances are inhomogeneous, the usual procedure would be to limit the working range. A weighted least squares fit is a rather complex algorithm for practical use. But for the special case that the change in the variances is proportional to $x_i$ – which is a common condition for measuring devices – the benefit of better results will amply compensate the effort.

Monitoring concepts commonly used on WWTPs (e.g. ATV-DVWK, 2000) suggest taking a sample once a week. In view of the required number of comparative measurements in the proposed concept, namely ten (and twenty for the homogeneity of the variances), at least 2.5 months of monitoring data would then be necessary. We therefore suggest that additional measurements should be made to characterize newly installed devices. The monitoring data should be available to calculate the uncertainties of sensors which were operated for a longer period of time. A problem arises if no information about external calibrations or changing conditions is available.

The effort required for the proposed concept with its preliminary checks and statistical tests seems rather high. However, its implementation in a software environment will allow rapid validation of the characterization values by statistical methods. It is important for the acceptance of the concept by the plant staff that the statistical results should be expressed in an understandable form. This means that plain language should be used instead of abstract mathematical expressions.

**CONCLUSIONS**

The proposed concept allows the uncertainty of continuously measuring devices to be quantified. Other concepts (e.g. ISO 15839, 2003; ISO 8466-1, 1990) describe methods of characterizing the devices themselves under standard conditions, whereas the proposed concept evaluates the whole measuring chain during field operation.

The concept will greatly increase the accuracy, reliability and acceptance of the measuring device. A knowledge of the trueness and precision of the devices under field conditions is made available to the plant operators, engineers and relevant authorities. This information allows control strategies to be better adapted to the processes and permits more sophisticated control concepts. Moreover, this concept can help to define guidelines for the evaluation of the accuracy of on-line devices so that continuously measuring devices can also be used for self surveillance (In Switzerland, the WWTPs are monitored with a combination of reference measurements issued by the authorities and a monitoring program located at the plant). This would lead to more reliable calculation of the effluent load and subsequently of the effluent tax thanks to the availability of dynamic data.

Future design and optimization studies should include knowledge about the uncertainties of the measuring devices. Dynamic simulation studies in particular have to rely on accurate continuously measured data (Langergraber et al., 2004). A knowledge of the uncertainty of the
input and output data will permit the use of probabilistic modelling. Explicit integration of the uncertainty will increase the transparency of the calculations and allow a risk evaluation within the scope of the design and optimization studies.

A non-commercial software package developed at EAWAG, which also contains our previously published monitoring concept (Thomann et al., 2001; Rieger et al., accepted), gave efficient hints on systematic as well as random errors. It was tested on different WWTPs in Switzerland with good results. It is a powerful tool and increased the knowledge and acceptance not only of the on-line devices but also of all the monitoring and control systems.

**APPENDIX**

**Relationship between sensor and reference measurement:**

A t-test with the following test statistic (eq. 5) is used on the 5% significance level (Draper and Smith, 1981). If \( PG > t_{f=n-2,0.975} \), the null hypothesis \( H_0: \beta=0 \), no correlation) has to be rejected, i.e. a significant relationship exists between the sensor and lab measurements.

\[
PG = \frac{\beta - \beta_0}{SE_{\beta}} = \frac{\beta}{SE_{\beta}}
\]

(5)

\[
SE_{\beta} = s_y \sqrt{\frac{1}{\sum_{i=1}^{n}(x_i - \bar{x})^2}}
\]

(6)

**Outlier elimination:**

The data with the highest absolute residual between the regression function and the measured sensor value is qualified as a potential outlier. A modified F-test (eq. 8, Funk et al., 1992) is used for the evaluation if the residual standard deviation significantly improves after elimination of this potential outlier (PO, eq. 7).

\[
P_O = \text{MAX} \bigg| y_i - \hat{y}_i \bigg| = \text{MAX} \bigg| y_i - (x_i \cdot \beta + \alpha) \bigg|
\]

(7)

\[
PG = \frac{f_{A_1} \cdot s_{y,A_1}^2 - f_{A_2} \cdot s_{y,A_2}^2}{s_{y,A_2}^2}
\]

where: \( A_1 = \) with outliers, \( A_2 = \) after outlier elimination

(8)

The test value PG is calculated with eq. 8 and compared with the values of the F-distribution \( (F(f_{A_1}=1, f_{A_2}=n_{A_2}-2, 0.99)) \). If \( PG > F_{f_1,f_2,0.99} \), the residual standard deviation has improved significantly and the data pair can be excluded. The test has to be repeated until no further outliers are detected.

As an alternative to the proposed method, a test according to Grubbs (e.g. Funk et al., 1985) is often used for outlier identification. An overview of other methods of detecting outliers can be found in Barnett and Lewis (1994).

**Linearity:**

The residual standard deviation of the two regression functions \( s_{y,1} \) linear function, \( s_{y,2} \) quadratic function: eq. 9) is analysed by means of an F-Test on a 1-% significance level (Funk et al., 1985). The test statistic PG is calculated with eq. 10. If \( PG > F_{f_1,f_2,0.99} \), the non-linear regression function fits the data significantly better.

\[
y = \beta_1 \cdot x + \beta_2 \cdot x^2 + \alpha
\]

(9)

\[
PG = \frac{DS^2}{s_{y,2}^2} \text{ with: } DS^2 = (n - 2) \cdot s_{y,1}^2 - (n - 3) \cdot s_{y,2}^2
\]

(10)
Uncertainties of On-line Sensors

Homogeneity of variances:
The residual standard deviations $s_y$ within an interval of 0-25% and 75-100% of the working range will be tested (eq. 11, Figure 5D). $s_y$ is calculated on the basis of a linear regression over all the data. The residual standard deviation $s_y$ quantifies the scattering of the measurements around the regression line. $s_y$ (eq. 11) is a measure of the precision, whereas the systematic error should be minimized by the linear regression parameters $\beta$ and $\alpha$.

$$s_y = \sqrt{\frac{\sum_{i=1}^{n} (y_i - \bar{y})^2}{n-2}} = \sqrt{\frac{\sum_{i=1}^{n} [y_i - (\beta \cdot x_i + \alpha)]^2}{n-2}}$$ (11)

$$PG = \frac{s_y_{0.75\%}^2}{s_y_{0.25\%}^2}$$ (12)

The test statistic $PG$ (eq. 12) will be compared with the value of the F-distribution on a 1% significance level ($F_{(f_1=n_{75\%}-1, f_2=n_{25\%}-1, 0.99)}$) If $PG > F_{(f_1,f_2,0.99)}$, the difference between the variances is significant.

Weighted linear regression:
Formulas for a weighted least squares fit according to Baird (1995):

$$\hat{\beta} = \frac{\sum_{i=1}^{n} w_i \cdot \sum_{i=1}^{n} (w_i \cdot x_i \cdot y_i) - \sum_{i=1}^{n} (w_i \cdot x_i) \cdot \sum_{i=1}^{n} (w_i \cdot y_i)}{\sum_{i=1}^{n} w_i \cdot \sum_{i=1}^{n} (w_i \cdot x_i^2) - \left(\sum_{i=1}^{n} (w_i \cdot x_i)\right)^2}$$

where $w_i = \frac{1}{s_{y,i}^2}$ (13)

$$\hat{\alpha} = \frac{\sum_{i=1}^{n} w_i \cdot (w_i \cdot y_i) \cdot \sum_{i=1}^{n} (w_i \cdot x_i^2) - \sum_{i=1}^{n} (w_i \cdot x_i) \cdot \sum_{i=1}^{n} (w_i \cdot x_i \cdot y_i)}{\sum_{i=1}^{n} w_i \cdot \sum_{i=1}^{n} (w_i \cdot x_i^2) - \left(\sum_{i=1}^{n} (w_i \cdot x_i)\right)^2}$$ (14)

REFERENCES


Funk W., Dammann V. and Donnevert G. (1992). Qualitätssicherung in der Analytischen Chemie. VCH, Weinheim [In German].


CHAPTER 4

PROGRESS IN SENSOR TECHNOLOGY – PROGRESS IN PROCESS CONTROL?
PART I:
SENSOR PROPERTY INVESTIGATION AND CLASSIFICATION

Leiv Rieger, Jens Alex, Stefan Winkler, Marc Böhler, Michael Thomann and Hansruedi Siegrist

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To ensure correctly operating control systems, the measurement and control equipment in WWTPs must be mutually consistent. The dynamic simulation of activated sludge systems could offer a suitable tool for designing and optimising control strategies. Ideal or simplified sensor models represent a limiting factor for comparability with field applications. More realistic sensor models are therefore required. Two groups of sensor models are proposed on the basis of field and laboratory tests: one for specific sensors and another for a classification of sensor types to be used with the COST simulation benchmark environment. This should lead to a more realistic test environment and allow control engineers to define the requirements of the measuring equipment as a function of the selected control strategy.

KEYWORDS
ASM, control of WWTPs, COST benchmark, sensor behaviour, sensor classes, sensor models

INTRODUCTION
In recent years, the importance of on-line measurements on WWTPs has increased noticeably and more reliable sensors have become available. Their main applications are in process control and for the continuous monitoring of effluent quality (Jeppson et al., 2002). Although these two applications have completely different requirements with regard to sensor behaviour, the same instruments are often used in both cases. High accuracy is needed for monitoring quality standards, although low demands are made on the time scale, whereas control applications mainly require a long measuring interval and a short response time. Recently developed nutrient sensors offer new perspectives for process control, but their limitations should be kept in mind. The time resolution may be essential for the control result, for example the inlet load variation must be measured quickly in feed-forward control to minimize the impact on the controlled processes. Finally, measurement noise may disturb the control behaviour.

The dynamic simulation of activated sludge systems (i.e. with the ASM family, Henze et al., 2000) is a proven tool for testing and optimising control strategies. The ideal (no delay or noise) or simplified (only delay) sensor models which are commonly used represent a limiting factor as regards comparability to field applications. Two groups of sensor models will be proposed in the following treatment: the first group describes specific sensors whose main characteristics have been determined. It is envisaged that this group be applied to optimise existing control systems consisting of measurement and control equipment. The second group of sensor models is designed with respect to the COST benchmark simulation framework (Alex et al., 1999; Copp, 2002). This framework was set up to test various control strategies in a standardised environment. Six classes of sensors are defined in order to specify the requirements of the
control strategies on the measuring system. In a second paper (Alex et al. 2003), the sensor models will be applied to simple and sophisticated aeration-control strategies in order to demonstrate the impact of the sensor behaviour on the control result.

SENSOR FIELD TESTS

A number of ammonium analysers were tested in the laboratory as well as in field applications. The laboratory tests included measurements of calibration standards and recovery experiments on the wastewater matrix. The field tests comprised the laboratory analysis of grab samples and determination of the response time of the measuring systems. The measurement results were processed in a database which is part of a software environment dealing with a monitoring concept for on-line analysers (Thomann et al., 2001). Control applications require the response time not only of the analyser but also of the entire measuring system including sample preparation where this exists. The study covered various methods for detecting the response time of the entire measuring system depending on the type of analyser (Table 1).

<table>
<thead>
<tr>
<th>No</th>
<th>Analyser</th>
<th>Filtration unit</th>
<th>Distance filt. – anal.</th>
<th>On/in-line</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Buoy type miniaturised photometric analyser</td>
<td>-</td>
<td>0 m</td>
<td>In-line</td>
</tr>
<tr>
<td>2</td>
<td>Photometric standard analyser</td>
<td>Continuous submerged membrane-type probe preparation</td>
<td>23 m</td>
<td>On-line</td>
</tr>
<tr>
<td>3</td>
<td>Photometric standard analyser</td>
<td>Discontinuous submerged membrane-type probe preparation</td>
<td>23 m</td>
<td>On-line</td>
</tr>
<tr>
<td>4</td>
<td>Flow-through cell type analyser with ion-sensitive electrodes</td>
<td>-</td>
<td>0 m</td>
<td>On-line</td>
</tr>
<tr>
<td>5</td>
<td>Gas-sensitive standard analyser</td>
<td>External membrane-type probe preparation</td>
<td>24 m</td>
<td>On-line</td>
</tr>
</tbody>
</table>

In general, the response (or T90) time (Figure 2 according to ISO/CD, 2000) of the sensors can be easily determined by switching between buckets containing test solutions of different concentrations. This test becomes more complicated for analysers requiring sample preparation, depending on the type of filtration unit. Analysers with a submerged filtration unit could be tested like in-line sensors subject to the required sample flow. A different method has to be used for external filtration units requiring a high sample flow rate. The inlet and return sludge flows of two lanes of a WWTP were stopped and digester supernatant was dosed into one lane in order to obtain two tanks with significantly different ammonium concentrations. The response time was determined by changing the sample supply pump from one lane to the other (Figure 1). Grab samples were taken over the test period to monitor the biodegradation.

Table 2 shows the results of the response time tests described as the T90 time (Figure 2). The buoy-type analyser could not be tested due to sensor failures. It should be borne in mind that all tested filtration units use new membrane technology, which affects the response time. Older units often have response times greater than 30 minutes. On this topic, it should also be noted that sample preparation systems require a high pump capacity and subsequently a high pump energy. This contradicts the goal of minimising the overall energy consumption by using optimised control systems based on on-line measurements.

<table>
<thead>
<tr>
<th>No</th>
<th>Analyser</th>
<th>Analyser only $T_{90}$ [min]</th>
<th>Analyser+filtration unit $T_{90}$ [min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Buoy-type miniaturised photometric analyser</td>
<td>-</td>
<td>9*</td>
</tr>
<tr>
<td>2</td>
<td>Photometric standard analyser with filtration unit</td>
<td>5</td>
<td>15</td>
</tr>
<tr>
<td>3</td>
<td>Photometric standard analyser with filtration unit</td>
<td>6</td>
<td>31**</td>
</tr>
<tr>
<td>4</td>
<td>Flow-through cell type analyser with ion-sensitive electrodes</td>
<td>-</td>
<td>&lt; 5 sec.</td>
</tr>
<tr>
<td>5</td>
<td>Gas-sensitive standard analyser with filtration unit</td>
<td>3</td>
<td>30***</td>
</tr>
</tbody>
</table>

*Manufacturer specification, **with discontinuous filtration, ***pump with only low flow rate (1 m³/h)
SENSOR MODELS

The following description of two kinds of sensor models is the result of a SIMULINK implementation and to some extent takes into account simulation performance issues which are similar for most simulation systems.

ASSUMPTIONS

First, some assumptions have to be made to ensure general applicability of the models and to keep them as simple as possible: the sensor response is linear over the entire measuring range; no systematic error is considered, since this would depend mainly on the maintenance and changing interference; and finally no attenuation is taken into account. If an attenuation is needed it can be defined within the tested controller.

Real measurement signals always include measurement noise, which can lead to unwanted control actions. A simplified noise description is included in the sensor models. The idea is not to model the noise exactly – this would make the model undesirably complex - but to take into account some of its effects. In order to obtain comparable simulation results for the COST benchmark or to have a basic definition of noise for the specific sensor model, a standard noise signal is defined in an ASCII file. If a random signal had been selected, it would have been necessary to run each simulation a large number of times in order to eliminate its influence. The noise signal has a normal distribution (standard deviation 1) and is frequency-limited. Use of a sample time of 1 minute together with linear interpolation will limit the frequency spectrum of the noise (cut-off of high frequencies - pink noise). The standard noise is then multiplied by the defined noise level (2.5% of the max. measuring range boundary for the benchmark models and user-defined for the specific sensor models). This simplification may run into problems, for instance if an autocorrelation has a significant impact on the control result. If measurements of the specific noise are available, these should be modelled instead.

SENSOR MODEL FOR SPECIFIC SENSORS

This sensor model describes sensors whose response time, measurement range (with the detection limit as the lower measurement range boundary), trueness and precision is known. The trueness is implemented optionally to test the robustness of the controller against measurement failures. The precision is calculated from a standard noise defined as the standard deviation at 20 and 80% of the measuring range. Moreover, a continuous drift effect which could be an
Sensor Models

An important source of unwanted control actions is modelled. An auto-calibration/auto-cleaning system and the measuring interval are also taken into account.

In the SIMULINK implementation (Figure 3) the raw sensor signal is transformed by a linear transfer function (block ‘Transfer Fcn for response time’) which is used to implement the step response of the sensor. The real-time behaviour of sensors is typically a combination of the delay time caused by sample transport and a dynamic part (rise/fall time) caused by a factor such as the hydraulic retention time of the analyser’s measuring chamber. The draft version of a future ISO standard (ISO/CD 2000) describing the performance of on-line sensors characterises the sensor dynamics based on a step response as presented in Figure 2. The (transport) delay time is defined as the time required to reach 10% of the final value of a step response ($T_{10}$). In this context, therefore, the delay time is not exactly the same as the transport delay time or dead time defined in control engineering. The overall time required to reach (and not to leave) a band between 90% - 110% of the final value of the step response is introduced as a response time (here $T_{90}$). For the sensor models, the desired dynamic time behaviour of the response time is modelled using a series of Laplace transfer functions. The number of first-order transfer functions in series ($n$) determines the ratio of delay time ($T_{10}$) to response time ($T_{90}$) (Figure 2).

$$G_{\text{sensor}}(s) = \frac{1}{(1 + T \cdot s)^n}$$

$G_{\text{Sensor}}$ = transfer function for response time

$T = T_{90}/\text{factor}$ = time constant to achieve defined $T_{90}$ time for a given $n$

$s = \text{Laplace operator, } n = \text{number of transfer functions in series}$

Figure 3: Simulink model of a specific sensor

Noise is considered by introducing the ‘standard’ noise signal, which is multiplied by the measuring range ($y_{\text{max}}-y_{\text{min}}$). The resulting signal is multiplied by a linear function defined by the noise offset $a$ and the slope $b$. This function is calculated depending on the defined noise levels at 20 and 80% (as a relative standard deviation) of the measuring range. The overall resulting noise signal is added to the output signal of the transfer function block.

A calibration and cleaning routine is modelled as a Simulink block containing a pulse generator (outputs 0 and 1). If the pulse falls from one to zero, the integrated drift error is reset to zero. During the calibration and cleaning routine, the last value is held using a switch block and another integrator as a memory function. A zero-order hold block is used to model the measuring interval of discontinuous sensors. This block must be deleted for continuous sensors. Figure 5 shows the original and sensor-model signals with the parameters from Figure 4.
It can be seen (Figure 5) that the noise varies depending on the actual measuring value due to the specification of the relative standard deviation at 20% (0.025) and 80% (0.2) of the measuring range. The continuous drift, the hold time during the calibration routine and the subsequent reset are clearly visible at the lower range. At the higher measuring range, the noise covers the drift effect.

Figure 6 shows the measured response time of the fifth system (gas-sensitive standard analyser with filtration unit) to a concentration step change and the results from the sensor model using a T90 time of 30 minutes and a relative standard deviation at 20 and 80% of the measuring range of 0.5%. No drift or calibration time were taken into account.

**SENSOR MODELS FOR THE COST SIMULATION BENCHMARK**

The aim of the classification is to describe different sensor types but also to limit the number of sensor classes in order to facilitate the comparison of the simulation results. The COST benchmark (Alex et al., 1999; Copp, 2002) is concerned with testing control strategies, so only a few related criteria are used. Thus drift effects are not considered because they would be too sensor-specific. Nevertheless, this procedure could easily be implemented for test reasons. There is no point in defining a user-configurable class, as this would make it difficult to compare different benchmark studies. It is assumed that even future sensors can be classified within the proposed scheme. Should it nevertheless be impossible to choose a class, the benchmark model user would be requested to describe the specific sensor in detail. The six sensor classes are shown in Table 3 and a list of typical sensors in Table 4.
Table 3: Suggested sensor classes

<table>
<thead>
<tr>
<th>Sensor classes</th>
<th>Response time [min]</th>
<th>Measuring interval [min]</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class A</td>
<td>1</td>
<td>0</td>
<td>Ion sensitive, optical without filtration</td>
</tr>
<tr>
<td>Class B₀</td>
<td>10</td>
<td>0</td>
<td>Gas sensitive + fast filtration</td>
</tr>
<tr>
<td>Class B₁</td>
<td>10</td>
<td>5</td>
<td>Photometric + fast filtration</td>
</tr>
<tr>
<td>Class C₀</td>
<td>20</td>
<td>0</td>
<td>Gas-sensitive + slow filtration</td>
</tr>
<tr>
<td>Class C₁</td>
<td>20</td>
<td>5</td>
<td>Photometric + slow filtration or sedimentation</td>
</tr>
<tr>
<td>Class D</td>
<td>30</td>
<td>30</td>
<td>Photometric or titrimetric for total components</td>
</tr>
</tbody>
</table>

The response time includes the whole system with the filtration unit and measuring system. Class A describes – from a control point of view – almost ideal sensors, the response time of 1 minute is chosen in order to prevent insufficiently realistic control applications. Class B mainly contains classical analysers with fast filtration and short sample loops. Class C describes analysers with a slow filtration or sedimentation unit. Class D includes all batch measurements including the respirometer and sensors for total components. To take into account continuously and discontinuously measuring sensors, classes B and C are subdivided into two subclasses. The measuring interval is defined as five minutes, this being a typical minimum value for photometric analysers. Longer intervals are not useful for control actions and are therefore neglected. In addition to choosing the sensor class, the user must define the measuring range for each sensor. Depending on the chosen measuring range, the standard deviation is calculated as approximately 2.5% of the maximum measuring-range boundary (see sensor model description).

The proposed sensor classes contain a set of continuous (A, B₀, C₀) and time-discrete sensor models (B₁, C₁, D). Continuous models are preferred to time-discrete ones for performance reasons. The discontinuous sensors B₁ and C₁ are modelled in a similar way but include an output sample and hold function. Sensor class D is modelled only in discrete form.

Table 4: Typical sensor characteristics within the proposed classification scheme

<table>
<thead>
<tr>
<th>Measured variable</th>
<th>Sensor types</th>
<th>Response time [min]</th>
<th>Measuring interval [min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>MLSS [g/l]</td>
<td>A</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Turbidity [FNU or mgTSS/l]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S_pHₐ (ionsensitive)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S_pHₐ (ionsensitive)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S_pHₐ (UV)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C_COD, S_COD (UV/Vis)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flow rate [m³/d]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water level [m]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature [°C]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>pH</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SO [mg O₂/l]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sludge blanket height [m]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S_pHₐ (gassensitive + fast filtration)</td>
<td>B₀</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>S_pHₐ (UV + fast filtration)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S_pHₐ (photometric + fast filtration)</td>
<td>B₁</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>S_COD (photometric + fast filtration)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S_SOC (photometric + fast filtration)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S_pHₐ (gassensitive + slow filtration)</td>
<td>C₀</td>
<td>20</td>
<td>0</td>
</tr>
<tr>
<td>S_pHₐ (UV + slow filtration)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S_pHₐ (photometric + slow filtration or sedimentation)</td>
<td>C₁</td>
<td>20</td>
<td>5</td>
</tr>
<tr>
<td>S_COD (photometric + slow filtration or sedimentation)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S_SOC (photometric + slow filtration or sedimentation)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C_COD (thermal chemical oxidation + photometric)</td>
<td>D</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>TOC (thermal oxidation + IR detector)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C_p (thermal oxid + IR detector or chemolumineszenz detector)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C_p (thermal chemical oxidation + photometric)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Respirometer</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Filtration biosensor (alkalinity)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
**Sensor Models**

Sensor model

1. **Signal Transfer Function for Response Time**
   
   \[ \text{Transfer Fcn for response time} \]

   \[ \text{Limitation to measuring range} \]

   \[ \text{Sensor model signal} \]

   **Noise width definition**

   \[ \text{Sensor noise} (1) \]

   **Noise file**

   **Limitation to measuring range**

   \[ \text{Raw signal} \]

   **Figure 7: Simulink model of classes A, B₀, C₀**

   **Figure 8: Step response of classes A, B₀, C₀**

**Continuously measuring sensors.** The following approach is suggested for classes A, B₀ and C₀. Table 5 shows the parameters for the response-time modelling (see specific sensor model) of the continuously operating sensors.

<table>
<thead>
<tr>
<th>Sensor class</th>
<th>T₁₀</th>
<th>n</th>
<th>T</th>
<th>R=T₁₀/T₉₀</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1 min</td>
<td>2</td>
<td>0.257</td>
<td>0.133</td>
</tr>
<tr>
<td>B₀</td>
<td>10 min</td>
<td>8</td>
<td>0.849</td>
<td>0.392</td>
</tr>
<tr>
<td>C₀</td>
<td>20 min</td>
<td>8</td>
<td>1.699</td>
<td>0.392</td>
</tr>
</tbody>
</table>

The transport delay for class A is only a small fraction of the response time typical for this sensor class. A system order of \( n=8 \) is assumed for sensor classes B and C, which leads to a delay time of approximately 40% of the response time. This is assumed to include the significant effect of the sample transport. The step responses for classes A, B₀ and C₀ are presented in Figure 8. The noise is modelled in a similar way to the specific sensor model, but only with a constant noise level \( n_l \). In the SIMULINK model presented in Figure 9, the noise signal is multiplied by the noise level \( n_l \) and the maximum value of the measurement interval \( y_{max} \). The noise is added to the delayed measurement signal and limited to the measurement interval \( (y_{min}, y_{max}) \). The noise level is defined as \( n_l=0.025 \) for all benchmark sensor classes (approx. 2.5% of the maximum boundary of the measuring range).

**Discontinuously measuring sensors.** Sensor classes B₁, C₁ and D are operated discontinuously using a sample time \( T₀ \). An example of an implementation using a SIMULINK model is presented in Figure 9. The implementation is similar to that used in the model for the continuously measuring sensors but includes an additional output sample and hold function.

**Figure 9: Simulink implementation class B₁, C₁**

**Figure 10: Simulink implementation class D**

Sensor class D represents batch-type reactors, for which any of the continuous delay times are negligible compared to the batch operation of the measurement. An appropriate SIMULINK implementation is demonstrated in Figure 10. This model adds noise to the original signal, limits the sum to the measuring range \( (y_{max} - y_{min}) \) and uses a sample and hold function followed by a unit delay \( (y(k)=u₃(k-1)) \). Figure 11 shows examples of the output signal for all sensor classes.

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59
CONCLUSIONS

Two groups of sensor models are proposed which allow a more realistic simulation of the control applications of activated sludge systems. The first group covers models for specific sensors. The main characteristics of existing sensors with respect to control applications are described. The aim is to choose a specific sensor or to optimise existing measurement and control systems. The control engineer can also test the robustness of his control strategy against systematic errors as well as noise effects. Under some basic assumptions such as linearity, the models include the response time, noise and drift as well as the calibration and cleaning intervals.

The second group of sensor models is designed for simulation benchmark studies. Various simulation benchmark systems such as the COST (Alex et al., 1999; Copp, 2002) or IWA benchmark (Copp et al., 2001) have been defined in recent years in order to compare different control strategies in a standardised environment. The widely used ideal or simplified sensor models represent a limiting factor for the comparability with field applications. A classification of sensor types and models is proposed in order to obtain more realistic and comparable results. A classification example for commonly used sensors is given. The sensor models are divided up into continuously and discontinuously operating ones, taking into account the response time, a measuring interval and a ‘standard’ noise. The width of the noise is defined as a standard deviation of 2.5% of the maximum measuring-range boundary. This should move the benchmark environment forward towards more applicable results. Moreover, it could also be an important step for optimisation studies using dynamic simulation because it will allow control engineers to define the requirements of the measuring equipment on the basis of the selected control strategy.

An investigation of the impact of sensor behaviour on various control strategies using the defined sensor classes is presented in Alex et al. (2003). A next step for even more realistic simulation results would be to model the response of the activated sludge system with respect to the controllers, for example a delay due to a limitation of the start/stop frequency of a blower.
REFERENCES


Copp J.B. (Editor) (2002). The COST simulation benchmark – Description and simulator manual. COST action 624, Office for official publications of the European Communities, Luxembourg.


CHAPTER 5

THE EAWAG BIO-P MODULE FOR ACTIVATED SLUDGE MODEL NO. 3

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The EAWAG Bio-P Module for Activated Sludge Model No. 3

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ABSTRACT

An additional module for the prediction of enhanced biological phosphorus removal is presented on the basis of a calibrated version of ASM3. The module uses modified processes from ASM2d but neglects the fermentation of readily degradable substrate. Biomass decay is modelled in the form of endogenous respiration as in ASM3. Moreover, an additional glycogen pool and biologically induced P-precipitation were not taken into account. The module was systematically calibrated with experimental data from various batch experiments, a full-scale WWTP and a pilot plant treating Swiss municipal wastewater. A standard parameter set allowed all data to be simulated.

KEYWORDS

Activated Sludge Model No. 3, ASM3, enhanced biological phosphorus removal, EBPR, Bio-P, nutrient removal, full-scale experiments, batch experiments

NOMENCLATURE

A  Autotrophic organisms
AAO anaerobic, anoxic, oxic: EBPR flow scheme
Bio-P EBPR
BPR Biological phosphorus removal
CSTR Continuous-stirred tank reactor
EBPR Enhanced biological phosphorus removal
end Endogenous respiration
H Heterotrophic organisms
HCO Bicarbonate
I Inert organic material
lys Lysis of PP
NH Ammonium+ammonia nitrogen
NO Nitrate+nitrite nitrogen
O Oxygen
PP Polyphosphate
PAO Phosphorus accumulating organisms
PHA Poly-hydroxy-alkanoates
resp Respiration
S Organic substrate, soluble component
SRT Sludge retention time
ThOD Theoretical oxygen demand
UCT University of Cape Town: EBPR flow scheme
X Particulate component

INTRODUCTION

Activated Sludge Model No. 3 (ASM3) (Henze et al., 2000) is a basic model made available by the IWA Task Group on Mathematical Modelling for Design and Operation of Biological Wastewater Treatment which can predict oxygen consumption, sludge production, nitrification and denitrification in activated sludge systems mainly treating municipal wastewater. ASM3 does not include biological phosphorus removal (BPR). In the first part of this paper an additional module for the BPR will be introduced, which is based on a calibrated version of ASM3 (Koch et al., 2000). An extensive calibration and validation of the EAWAG Bio-P module is presented in the second part of the paper.
PART ONE: MODEL DEFINITION

This paper describes only components and processes relating to the biological phosphorus removal. Hydrolysis, heterotrophic and autotrophic processes are modelled exactly as in ASM3 (Henze et al., 2000 and Koch et al., 2000), but with limitations for phosphorus in all growth processes.

DEFINITION OF COMPONENTS

The EAWAG Bio-P module requires four state variables in addition to the 13 components defined in ASM3 to model the biological phosphorus removal. In contrast to the IAWQ model ASM2d (Henze et al., 2000), which considers BPR, the module discussed here neglects the fermentation of the readily degradable substrate. It is assumed on the basis of a statistic model analysis and research results (Satoh et al., 1996, Mino et al., 1998) that there is no limitation of the P-release due to the fermentation process in typical municipal wastewater. To keep the model simple, only one internal substrate pool is modelled and an additional glycogen pool is neglected. Although this differs from other research results (Satoh et al., 1996, Mino et al., 1995, 1998), measurements in pilot and full-scale experiments in Swiss municipal wastewater did not show the expected significant influence of glycogen on the EBPR process and therefore the authors consider a model including glycogen unnecessary complex. This assumption is to be seen with a view to diluted Swiss municipal wastewater under typical conditions. The simplification was tested against data from situations with a low COD load, i.e. after weekends (Carucci et al., 1999, Brdjanovic et al., 1998), where glycogen limitation could play a crucial role.

The four additional components for the EAWAG Bio-P module are identical to the components used in ASM2d (Henze et al., 2000):

- **SPO₄ [M (P) L⁻³]**: Inorganic soluble phosphorus, primarily ortho-phosphates. In order to simplify the balance of electrical charges, it is assumed that \( S_{PO₄} \) consists of 50% \( H_2PO_4^- \) and 50% \( HPO_4^{2-} \) and therefore has an electric charge of \(-1.5/31\).

- **XPₐo [M (COD) L⁻³]**: Phosphorus accumulating organisms: PAO. These organisms are assumed to be representative for all types of polyphosphate accumulating organisms. They are all assumed to grow aerobically and some of them anoxically. The concentration of \( X_{PAO} \) does not include the cell-internal storage products \( X_{PP} \) and \( X_{PHA} \), but only the ‘true’ biomass.

- **XPHA [M (COD) L⁻³]**: This is a cell-internal storage product of phosphorus-accumulating organisms. It primarily includes poly-hydroxy-alkanoates (PHA) and glycogen. Although it occurs only in association with \( X_{PAO} \), it is not included in the mass of \( X_{PAO} \). \( X_{PHA} \) cannot be compared directly with analytically measured PHA concentrations; it is a functional component required for modelling but cannot be directly identified in chemical terms. However, it is recovered in COD analysis, where it must satisfy ThOD conservation. For stoichiometric considerations, \( X_{PHA} \) is assumed to have the chemical composition of poly-hydroxy-butyrate \((C_4H_6O_2)_n\).

- **XPP [M (P) L⁻³]**: Polyphosphate. This is a cell-internal inorganic storage product of PAO. It is assumed to be associated only with \( X_{PAO} \) but is not included in the latter’s mass. It forms part of the particulate phosphorus and may be analytically observed. For stoichiometric considerations, poly-phosphate is assumed to have the composition of \((K_{0.34}Mg_{0.33}PO_3)_n\). Since the Bio-P module does not account for \( K^+ \) and \( Mg^{2+} \), an electric charge of \(-1/31\) must be included to compensate for this term.
DEFINITION OF PROCESSES

The **EAWAG Bio-P module** adds biological phosphorus removal to ASM3, i.e. the physiological phosphorus uptake during the growth of organisms as well as the enhanced biological phosphorus removal (EBPR) of the PAO. For the physiological phosphorus uptake, the growth processes of ASM3 must be completed by terms for phosphorus limitation. The EBPR could be described by 11 additional processes. Besides neglecting fermentation, the main differences in comparison to ASM2d are the use of endogenous respiration and the lower rates of anoxic compared to aerobic decay. The anaerobic decay is minimal and is therefore neglected. This assumption results from batch experiments under starvation conditions (Siegrist *et al.*, 1999). Another assumption is that the biologically induced but inorganic calcium-phosphate precipitation in the anaerobic tank is not considered in the model. At pH < 7.5 and temperatures $T < 20^\circ\text{C}$, which prevail in many municipal plants, no relevant biologically induced phosphorus precipitation is expected (Maurer *et al.*, 1999). The Bio-P module does not include chemical precipitation, but the two processes considered in ASM2d could easily be implemented.

The following processes are similar to the ones in ASM2d (Henze *et al.*, 2000), but with the modifications mentioned above:

- **Storage of $X_{\text{PHA}}$ (process P1):** This process describes the storage of readily degradable substrate ($S_S$) in the form of cell-internal storage products ($X_{\text{PHA}}$). The storage is connected directly to the P-release by the stoichiometric parameter $Y_{PO4}$. The energy that becomes available during the release of polyphosphate ($X_{pp}$) is used to store the substrate.

  This process occurs mainly under anaerobic conditions but is also observed in aerobic and anoxic zones. For this reason, no inhibition terms are implemented in the kinetic expression. The influence of oxygen or nitrate on the P-release is modelled only with a substrate competition between PAO and other heterotrophs.

- **Aerobic (P2) and anoxic (P3) storage of $X_{pp}$:** The PAO require energy for the uptake of orthophosphate ($S_{PO4}$) and its storage in the form of cell-internal polyphosphates ($X_{pp}$). This energy can be obtained from the aerobic or anoxic respiration of $X_{\text{PHA}}$. The regeneration of the $X_{pp}$-pool is essential for the growth of PAO because the substrate uptake only occurs in parallel with the P-release. An inhibition term is implemented to take a maximum P-content of the PAO into account. It becomes active when the $X_{pp} / X_{PAO}$ ratio approaches the maximum permissible value of $K_{\text{max}}$.

  During the anoxic P-storage, nitrate is respired instead of oxygen. A reduction factor ($\eta_{\text{NO,PAO}}$) is introduced because not all PAO are capable of denitrification, which may only proceed at a reduced rate compared with aerobic storage.
Table 1: Stoichiometric matrix for the soluble components of ASM3 (Henze et al., 2000) and the EAWAG Bio-P module, n: stoich. coeff., j: process, i: components, nj,HCO and nj,TSS from charge and mass conservation (Gujer & Larsen, 1995).

<table>
<thead>
<tr>
<th>j Processes</th>
<th>i Processes</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrolysis</td>
<td>S0, (gO₂ m⁻³)</td>
<td>S1, (gCOD m⁻³)</td>
<td>S2, (gN m⁻³)</td>
<td>S30, (gN m⁻³)</td>
<td>S31, (gCOD m⁻³)</td>
<td>S32, (gN m⁻³)</td>
<td>S33, (gP m⁻³)</td>
<td>S34, (mol m⁻³)</td>
<td></td>
</tr>
<tr>
<td>Heterotrophic organisms X₉O</td>
<td>fₛₖ</td>
<td>fₛ</td>
<td>kₓₓₛₖ,ₙₛₖ(ᵣₛₖ) - kₓₓₛₖ</td>
<td>kₓₚₛₖ</td>
<td>kₓₚₛₖ</td>
<td>fₛₙₛₖ</td>
<td>fₛₙₛₖ</td>
<td>fₛₙₛₖ</td>
<td>fₛₙₛₖ</td>
</tr>
<tr>
<td>Aer. storage of X₉O</td>
<td>Yₓₓₛₖ₀,₁ -1</td>
<td>-1</td>
<td>kₓₛₖ</td>
<td>kₓₛₖ</td>
<td>(1 - fₛₙₛₖ)²/2.86</td>
<td>(1 - fₛₙₙₛₖ)²/2.86</td>
<td>Yₓₓₛₖ₀,₁</td>
<td>Yₓₓₛₖ₀,₁</td>
<td></td>
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<td>Anox. storage of X₉O</td>
<td>1 - Yₓₓₛₖ₀,₁</td>
<td>-1</td>
<td>kₓₛₖ</td>
<td>kₓₛₖ</td>
<td>(1 - fₛₙₛₖ)²/2.86</td>
<td>(1 - fₛₙₙₛₖ)²/2.86</td>
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<td>Yₓₓₛₖ₀,₁</td>
<td></td>
</tr>
<tr>
<td>Aerobic growth</td>
<td>1 - Yₓₓₛₖ₀,₁</td>
<td>-1</td>
<td>kₓₛₖ</td>
<td>kₓₛₖ</td>
<td>(1 - fₛₙₛₖ)²/2.86</td>
<td>(1 - fₛₙₙₛₖ)²/2.86</td>
<td>Yₓₓₛₖ₀,₁</td>
<td>Yₓₓₛₖ₀,₁</td>
<td></td>
</tr>
<tr>
<td>Anoxic growth</td>
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<td>-1</td>
<td>kₓₛₖ</td>
<td>kₓₛₖ</td>
<td>(1 - fₛₙₛₖ)²/2.86</td>
<td>(1 - fₛₙₙₛₖ)²/2.86</td>
<td>Yₓₓₛₖ₀,₁</td>
<td>Yₓₓₛₖ₀,₁</td>
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<tr>
<td>Anox. endog. respiration</td>
<td>(1 - fₛₙₙₛₖ)²/2.86</td>
<td>(1 - fₛₙₙₛₖ)²/2.86</td>
<td>Yₓₓₛₖ₀,₁</td>
<td>Yₓₓₛₖ₀,₁</td>
<td></td>
<td></td>
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<td>Aer. endog. respiration</td>
<td>(1 - fₛₙₙₛₖ)²/2.86</td>
<td>(1 - fₛₙₙₛₖ)²/2.86</td>
<td>Yₓₓₛₖ₀,₁</td>
<td>Yₓₓₛₖ₀,₁</td>
<td></td>
<td></td>
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<tr>
<td>Aer. resp. of X₉O</td>
<td>(1 - fₛₙₙₛₖ)²/2.86</td>
<td>(1 - fₛₙₙₛₖ)²/2.86</td>
<td>Yₓₓₛₖ₀,₁</td>
<td>Yₓₓₛₖ₀,₁</td>
<td></td>
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<tr>
<td>Anox. resp. of X₉O</td>
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<td>(1 - fₛₙₙₛₖ)²/2.86</td>
<td>Yₓₓₛₖ₀,₁</td>
<td>Yₓₓₛₖ₀,₁</td>
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<td></td>
<td></td>
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<tr>
<td>Anoxic organisms X₅O</td>
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<td>-1</td>
<td>kₓₛₖ</td>
<td>kₓₛₖ</td>
<td>(1 - fₛₙₛₖ)²/2.86</td>
<td>(1 - fₛₙₙₛₖ)²/2.86</td>
<td>Yₓₓₛₖ₀,₁</td>
<td>Yₓₓₛₖ₀,₁</td>
<td></td>
</tr>
<tr>
<td>Aer. endog. respiration</td>
<td>(1 - fₛₙₙₛₖ)²/2.86</td>
<td>(1 - fₛₙₙₛₖ)²/2.86</td>
<td>Yₓₓₛₖ₀,₁</td>
<td>Yₓₓₛₖ₀,₁</td>
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<tr>
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<td>(1 - fₛₙₙₛₖ)²/2.86</td>
<td>Yₓₓₛₖ₀,₁</td>
<td>Yₓₓₛₖ₀,₁</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Storage of X₈O</td>
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<td>kₓₛₖ</td>
<td>kₓₛₖ</td>
<td>(1 - fₛₙₛₖ)²/2.86</td>
<td>(1 - fₛₙₙₛₖ)²/2.86</td>
<td>Yₓₓₛₖ₀,₁</td>
<td>Yₓₓₛₖ₀,₁</td>
<td></td>
</tr>
<tr>
<td>Aerobic storage of X₈O</td>
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<td>-1</td>
<td>kₓₛₖ</td>
<td>kₓₛₖ</td>
<td>(1 - fₛₙₛₖ)²/2.86</td>
<td>(1 - fₛₙₙₛₖ)²/2.86</td>
<td>Yₓₓₛₖ₀,₁</td>
<td>Yₓₓₛₖ₀,₁</td>
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<tr>
<td>Anox. storage of X₈O</td>
<td>1 - Yₓₓₛₖ₀,₁</td>
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<td>kₓₛₖ</td>
<td>kₓₛₖ</td>
<td>(1 - fₛₙₛₖ)²/2.86</td>
<td>(1 - fₛₙₙₛₖ)²/2.86</td>
<td>Yₓₓₛₖ₀,₁</td>
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<tr>
<td>Aerobic growth</td>
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<td>kₓₛₖ</td>
<td>kₓₛₖ</td>
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<td>(1 - fₛₙₙₛₖ)²/2.86</td>
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<td>Anoxic growth</td>
<td>1 - Yₓₓₛₖ₀,₁</td>
<td>-1</td>
<td>kₓₛₖ</td>
<td>kₓₛₖ</td>
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<td>(1 - fₛₙₙₛₖ)²/2.86</td>
<td>Yₓₓₛₖ₀,₁</td>
<td>Yₓₓₛₖ₀,₁</td>
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</tr>
<tr>
<td>Anox. endog. respiration</td>
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<td>(1 - fₛₙₙₛₖ)²/2.86</td>
<td>Yₓₓₛₖ₀,₁</td>
<td>Yₓₓₛₖ₀,₁</td>
<td></td>
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</tr>
<tr>
<td>Anox. resp. of X₈O</td>
<td>(1 - fₛₙₙₛₖ)²/2.86</td>
<td>(1 - fₛₙₙₛₖ)²/2.86</td>
<td>Yₓₓₛₖ₀,₁</td>
<td>Yₓₓₛₖ₀,₁</td>
<td></td>
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<tr>
<td>Aer. resp. of X₈O</td>
<td>(1 - fₛₙₙₛₖ)²/2.86</td>
<td>(1 - fₛₙₙₛₖ)²/2.86</td>
<td>Yₓₓₛₖ₀,₁</td>
<td>Yₓₓₛₖ₀,₁</td>
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</tr>
<tr>
<td>Phosphorus accumulating organisms X₉P</td>
<td>P1 Storage of X₈P</td>
<td>-1</td>
<td>kₓₛₖ</td>
<td>kₓₛₖ</td>
<td>(1 - fₛₙₛₖ)²/2.86</td>
<td>(1 - fₛₙₙₛₖ)²/2.86</td>
<td>Yₓₓₛₖ₀,₁</td>
<td>Yₓₓₛₖ₀,₁</td>
<td></td>
</tr>
<tr>
<td>P2 Aerobic storage of X₈P</td>
<td>-1</td>
<td>kₓₛₖ</td>
<td>kₓₛₖ</td>
<td>(1 - fₛₙₛₖ)²/2.86</td>
<td>(1 - fₛₙₙₛₖ)²/2.86</td>
<td>Yₓₓₛₖ₀,₁</td>
<td>Yₓₓₛₖ₀,₁</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P3 Anox. storage of X₈P</td>
<td>1 - Yₓₓₛₖ₀,₁</td>
<td>-1</td>
<td>kₓₛₖ</td>
<td>kₓₛₖ</td>
<td>(1 - fₛₙₛₖ)²/2.86</td>
<td>(1 - fₛₙₙₛₖ)²/2.86</td>
<td>Yₓₓₛₖ₀,₁</td>
<td>Yₓₓₛₖ₀,₁</td>
<td></td>
</tr>
<tr>
<td>P4 Aerobic growth</td>
<td>1 - Yₓₓₛₖ₀,₁</td>
<td>-1</td>
<td>kₓₛₖ</td>
<td>kₓₛₖ</td>
<td>(1 - fₛₙₛₖ)²/2.86</td>
<td>(1 - fₛₙₙₛₖ)²/2.86</td>
<td>Yₓₓₛₖ₀,₁</td>
<td>Yₓₓₛₖ₀,₁</td>
<td></td>
</tr>
<tr>
<td>P5 Anoxic growth</td>
<td>1 - Yₓₓₛₖ₀,₁</td>
<td>-1</td>
<td>kₓₛₖ</td>
<td>kₓₛₖ</td>
<td>(1 - fₛₙₛₖ)²/2.86</td>
<td>(1 - fₛₙₙₛₖ)²/2.86</td>
<td>Yₓₓₛₖ₀,₁</td>
<td>Yₓₓₛₖ₀,₁</td>
<td></td>
</tr>
<tr>
<td>P6 Anox. endog. respiration</td>
<td>(1 - fₛₙₙₛₖ)²/2.86</td>
<td>(1 - fₛₙₙₛₖ)²/2.86</td>
<td>Yₓₓₛₖ₀,₁</td>
<td>Yₓₓₛₖ₀,₁</td>
<td></td>
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</tr>
<tr>
<td>P7 Anox. resp. of X₈P</td>
<td>(1 - fₛₙₙₛₖ)²/2.86</td>
<td>(1 - fₛₙₙₛₖ)²/2.86</td>
<td>Yₓₓₛₖ₀,₁</td>
<td>Yₓₓₛₖ₀,₁</td>
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</tr>
<tr>
<td>P8 Aerobic lysis of X₈P</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
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</tr>
<tr>
<td>P9 Anox. lysis of X₈P</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
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</tr>
<tr>
<td>P10 Aer. resp. of X₈P</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
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<tr>
<td>P11 Anox. resp. of X₈P</td>
<td>1</td>
<td>1</td>
<td>1</td>
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Composition matrix

<table>
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<tr>
<th>Conserves</th>
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<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
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<tr>
<td>ThOD g ThOD</td>
<td>-1</td>
<td>1</td>
<td>1</td>
<td>-64/14</td>
<td>-24/14</td>
</tr>
<tr>
<td>Nitrogen g N</td>
<td>kₓₛₖ</td>
<td>kₓₛₖ</td>
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<tr>
<td>Phosphorus g P</td>
<td>kₓₛₖ</td>
<td>kₓₛₖ</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Ionic charge Mole +</td>
<td>1/14</td>
<td>-1/14</td>
<td>-1.531</td>
<td>-1</td>
<td></td>
</tr>
</tbody>
</table>

Observables

| SS g SS | 5 |

* In this model, it is assumed that ThOD is identical to the measured COD. Definition: 1 g S₀ = -1 g ThOD, 1 g S₉₆ = 0 g ThOD, 1 g S₃₀ = -64/14g ThOD and 1 g S₉₆ = -24/14g ThOD.
Table 2: Stoichiometric matrix for the particulate components of ASM3 (Henze et al., 2000) and the EAWAG Bio-P module

<table>
<thead>
<tr>
<th>Model components i</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
<th>16</th>
<th>17</th>
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<tr>
<td>j Processes</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>1 Hydrolysis</td>
<td>-1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 Heterotrophic organisms Xh</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>3 Anox. storage of $X_{STO}$</td>
<td>$\nu_{STO}$</td>
<td>$\nu_{STO}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 Aerobic growth</td>
<td>1</td>
<td>-1/$\nu_{LO}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 Anoxic growth</td>
<td>1</td>
<td>-1/$\nu_{LO}$</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>6 Aer. endog. respiration $f_{a}$</td>
<td>-1</td>
<td></td>
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<tr>
<td>7 Anox. endog. respiration $f_{a}$</td>
<td>-1</td>
<td></td>
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<td></td>
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<td></td>
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</tr>
<tr>
<td>8 Aer. resp. of $X_{STO}$ -1</td>
<td></td>
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<td></td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>9 Anox. resp. of $X_{STO}$ -1</td>
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<tr>
<td>10 Growth</td>
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<td>11 Aer. endog. respiration $f_{a}$</td>
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<td>12 Anox. endog. respiration $f_{a}$</td>
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<td></td>
<td></td>
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<tr>
<td>13 Phosphorus accumulating organisms Xp</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P1 Storage of $X_{PHA}$</td>
<td>-$\nu_{PHA}$</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>P2 Aerobic storage of $X_{PP}$</td>
<td>1</td>
<td>-$\nu_{PHA}$</td>
<td>1</td>
<td>-$\nu_{PHA}$</td>
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</tr>
<tr>
<td>P3 Anox. storage $X_{PP}$</td>
<td>1</td>
<td>-$\nu_{PHA}$</td>
<td>1</td>
<td>-$\nu_{PHA}$</td>
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</tr>
<tr>
<td>P4 Aerobic growth</td>
<td>1</td>
<td>-$\nu_{PHA}$</td>
<td>1</td>
<td>-$\nu_{PHA}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P5 Anox. growth</td>
<td>1</td>
<td>-$\nu_{PHA}$</td>
<td>1</td>
<td>-$\nu_{PHA}$</td>
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<td></td>
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<tr>
<td>P6 Aer. endog. respiration $f_{a}$</td>
<td>-1</td>
<td></td>
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<tr>
<td>P7 Anox. endog. respiration $f_{a}$</td>
<td>-1</td>
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<td></td>
</tr>
<tr>
<td>P8 Aerobic lysis of $X_{PP}$</td>
<td>-1</td>
<td></td>
<td></td>
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<tr>
<td>P9 Anox. lysis of $X_{PP}$ -1</td>
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<tr>
<td>P10 Aer. resp. of $X_{PHA}$ -1</td>
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<td></td>
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<tr>
<td>P11 Anox. resp. of $X_{PHA}$ -1</td>
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<td></td>
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<td></td>
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<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

Composition matrix

Conservatives

| 1 | $ThOD$ gThOD | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 2 | Nitrogen g N | $i_{N,XS}$ | $i_{N,XS}$ | $k_{BM}$ | $k_{BM}$ | 1 | 1 |
| 3 | Phosphorus g P | $i_{P,XI}$ | $i_{P,XS}$ | $k_{BM}$ | $k_{BM}$ | 1 | 1 |
| 4 | Ionic charge Mole | $i_{BM}$ | $i_{BM}$ | $i_{MLAM}$ | $i_{MLAM}$ | 3.23 | $i_{MLAM}$ | $i_{MLAM}$ | -1 |

Observables

| 5 | TSS g TSS | $i_{TSS,XS}$ | $i_{TSS,XS}$ | $i_{TSS,BM}$ | $i_{TSS,BM}$ | 3.23 | $i_{TSS,BM}$ | $i_{TSS,BM}$ | -1 |
**EAWAG Bio-P Module**

Table 3: Kinetic rate expressions for the **EAWAG Bio-P module**

<table>
<thead>
<tr>
<th>No.</th>
<th>Process</th>
<th>Process rate equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>Storage of X&lt;sub&gt;PHA&lt;/sub&gt;</td>
<td>( \eta_{PHA} \frac{S_o}{K_{PHA} + S_o} \frac{S_{HCO}}{K_{HCO,PHA} + S_{HCO}} \frac{S_{PO}<em>{4}}{K</em>{PO}<em>{4,PHA} + S</em>{PO}<em>{4}} X</em>{PHA} X_{PAO} )</td>
</tr>
<tr>
<td>P2</td>
<td>Aer. storage of X&lt;sub&gt;PP&lt;/sub&gt;</td>
<td>( \eta_{PP} \frac{K_{PP,PHA}}{K_{O,PHA} + S_o} \frac{S_{NO}<em>{3}}{K</em>{NO,PHA} + S_{NO}<em>{3}} \frac{S</em>{PO}<em>{4}}{K</em>{PO}<em>{4,PHA} + S</em>{PO}<em>{4}} X</em>{PHA} X_{PAO} )</td>
</tr>
<tr>
<td>P3</td>
<td>Anox. storage of X&lt;sub&gt;PP&lt;/sub&gt;</td>
<td>( \eta_{NO,PHA} \frac{K_{NO,PHA}}{K_{NO,PHA} + S_{NO}} \frac{S_{PO}<em>{4}}{K</em>{PO}<em>{4,PHA} + S</em>{PO}<em>{4}} X</em>{PHA} X_{PAO} )</td>
</tr>
<tr>
<td>P4</td>
<td>Aer. growth of X&lt;sub&gt;PHA&lt;/sub&gt;</td>
<td>b&lt;sub&gt;PHA&lt;/sub&gt; ( \frac{S_o}{K_{PHA} + S_o} X_{PAO} )</td>
</tr>
<tr>
<td>P5</td>
<td>Anox. growth of X&lt;sub&gt;PHA&lt;/sub&gt;</td>
<td>b&lt;sub&gt;NO,PHA&lt;/sub&gt; ( \frac{K_{NO,PHA}}{K_{NO,PHA} + S_{NO}} \frac{S_{PO}<em>{4}}{K</em>{PO}<em>{4,PHA} + S</em>{PO}<em>{4}} X</em>{PHA} X_{PAO} )</td>
</tr>
<tr>
<td>P6</td>
<td>Aerobic endog. respiration</td>
<td>b&lt;sub&gt;PHA&lt;/sub&gt; ( \frac{S_o}{K_{PHA} + S_o} X_{PAO} )</td>
</tr>
<tr>
<td>P7</td>
<td>Anoxic endog. respiration</td>
<td>b&lt;sub&gt;NO,PHA&lt;/sub&gt; ( \frac{K_{NO,PHA}}{K_{NO,PHA} + S_{NO}} \frac{S_{PO}<em>{4}}{K</em>{PO}<em>{4,PHA} + S</em>{PO}<em>{4}} X</em>{PHA} X_{PAO} )</td>
</tr>
<tr>
<td>P8</td>
<td>Aerobic lysis of X&lt;sub&gt;PP&lt;/sub&gt;</td>
<td>b&lt;sub&gt;PP&lt;/sub&gt; ( \frac{S_o}{K_{PP,PHA} + S_o} X_{PP} )</td>
</tr>
<tr>
<td>P9</td>
<td>Anoxic lysis of X&lt;sub&gt;PP&lt;/sub&gt;</td>
<td>b&lt;sub&gt;NO,PP&lt;/sub&gt; ( \frac{K_{NO,PP}}{K_{NO,PP} + S_{NO}} \frac{S_{PP}}{K_{PP,PHA} + S_{PP}} X_{PP} )</td>
</tr>
<tr>
<td>P10</td>
<td>Aerobic resp. of X&lt;sub&gt;PHA&lt;/sub&gt;</td>
<td>b&lt;sub&gt;PHA&lt;/sub&gt; ( \frac{S_o}{K_{PHA} + S_o} X_{PHA} )</td>
</tr>
<tr>
<td>P11</td>
<td>Anoxic resp. of X&lt;sub&gt;PHA&lt;/sub&gt;</td>
<td>b&lt;sub&gt;NO,PHA&lt;/sub&gt; ( \frac{K_{NO,PHA}}{K_{NO,PHA} + S_{NO}} \frac{S_{NO}}{K_{NO,PHA} + S_{NO}} X_{PHA} )</td>
</tr>
</tbody>
</table>

**Aerobic (P4) and anoxic (P5) growth of X<sub>PAO</sub>:** In this model, it is assumed that PAO grow only on cell-internal storage products (X<sub>PHA</sub>). For the anoxic growth of PAO, the same reduction factor (\( \eta_{NO,PHA} \)) is used as in process P3.

**Aerobic (P6) and anoxic (P7) endogenous respiration:** These processes, which are introduced in ASM3, describe all forms of biomass loss and energy requirements not associated with growth by considering the related respiration under aerobic and anoxic conditions: decay, (maintenance), endogenous respiration, lysis, predation, motility, death, etc. The anoxic endogenous respiration is similar to the aerobic process, but includes the reduction factor \( \eta_{NO,\text{end,PAO}} \).

**Aerobic (P8, P10) and anoxic (P9, P11) respiration and lysis of internal storage products:** These processes are analogous to the endogenous respiration of the biomass, which ensures that the storage products decay together with the biomass. The anoxic processes are reduced by the factors \( \eta_{NO,\text{resp,PAO}} \) and \( \eta_{NO,\text{lys,PAO}} \).

**STOICHIOMETRY**

A stoichiometric matrix for ASM3 together with the **EAWAG Bio-P module** is shown in Tables 1 and 2. All stoichiometric parameters are explained and listed in Table 4. The main difference in comparison to ASM2d is the distinction between aerobic and anoxic yields, as introduced in ASM3. In contrast to the original version of ASM3 (Henze et al., 2000), the calibrated version (Koch et al., 2000) uses fitted aerobic and anoxic storage (Y<sub>STO</sub>) and growth (Y<sub>11</sub>) yields based on batch experiments instead of a constant reduction factor for the anoxic energy yields (Table 8). The yields of the PAO are calibrated with batch experiments.

70
Table 4: Kinetic parameters for the EAWAG Bio-P module at $T=T_{20°C}$ with exponential temperature dependence $θ_T$ (after slash). Values differing from the ASM2d (Henze et al., 2000) are shown in bold print.

| Kinetic parameters                          | Symbol | Unit              | Default value ASM2d/$θ_T$ | EAWAG Bio-P module/$θ_T$
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Rate constant for storage of $X_{PHA}$</td>
<td>$q_{PHA}$</td>
<td>d$^{-1}$</td>
<td>3/0.04</td>
<td>6/0.04</td>
</tr>
<tr>
<td>Rate constant for storage of $X_{TP}$</td>
<td>$q_{TP}$</td>
<td>d$^{-1}$</td>
<td>1.5/0.04</td>
<td>1.5/0.04</td>
</tr>
<tr>
<td>Max. growth rate of $X_{XG}$</td>
<td>$μ_{XG}$</td>
<td>d$^{-1}$</td>
<td>1/0.07</td>
<td>1/0.07</td>
</tr>
<tr>
<td>Anoxic reduction factor growth of $X_{PAO}$</td>
<td>$η_{NO,PAO}$</td>
<td>-</td>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>Max. endogenous respiration rate of $X_{PAO}$</td>
<td>$b_{NO}$</td>
<td>d$^{-1}$</td>
<td>0.2/0.07</td>
<td>0.2/0.07</td>
</tr>
<tr>
<td>Anoxic reduction factor for endog. respiration</td>
<td>$η_{NO,PAO}$</td>
<td>-</td>
<td>0.33</td>
<td>-</td>
</tr>
<tr>
<td>Lysis $X_{TP}$</td>
<td>$b_{LY}$</td>
<td>d$^{-1}$</td>
<td>0.2/0.07</td>
<td>0.2/0.07</td>
</tr>
<tr>
<td>Anoxic reduction factor for lysis</td>
<td>$η_{NO,LY}$</td>
<td>-</td>
<td>0.33</td>
<td>-</td>
</tr>
<tr>
<td>Respiration rate for $X_{PHA}$</td>
<td>$b_{PHA}$</td>
<td>d$^{-1}$</td>
<td>0.2/0.07</td>
<td>0.2/0.07</td>
</tr>
<tr>
<td>Anoxic reduction factor for respiration</td>
<td>$η_{NO,PHA}$</td>
<td>-</td>
<td>0.33</td>
<td>-</td>
</tr>
<tr>
<td>Saturation constant for $S_i$</td>
<td>$K_{S_i,PAO}$</td>
<td>gCOD m$^{-3}$</td>
<td>4</td>
<td>10</td>
</tr>
<tr>
<td>Saturation constant for $S_{HCO}$</td>
<td>$K_{HCO,PAO}$</td>
<td>mol m$^{-3}$</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Saturation constant for $X_{TP}/X_{PAO}$</td>
<td>$K_{TP,PAO}$</td>
<td>gP gCOD$^{-1}$</td>
<td>0.01</td>
<td>0.05</td>
</tr>
<tr>
<td>Saturation constant for $X_{XG}$</td>
<td>$K_{XG}$</td>
<td>gO$_2$ m$^{-3}$</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Saturation constant for $X_{PHA}/X_{PAO}$</td>
<td>$K_{PHA}$</td>
<td>gCOD gCOD$^{-1}$</td>
<td>0.01</td>
<td>0.1</td>
</tr>
<tr>
<td>Maximum ratio of $X_{TP}/X_{NO}$</td>
<td>$K_{TP,NO}$</td>
<td>gP gCOD$^{-1}$</td>
<td>0.34</td>
<td>0.2</td>
</tr>
<tr>
<td>Saturation constant for $[K_{TP,PAO}/(X_{TP}/X_{PAO})]$</td>
<td>$K_{TP,PAO}$</td>
<td>gP gCOD$^{-1}$</td>
<td>0.02</td>
<td>0.05</td>
</tr>
<tr>
<td>Saturation constant for $S_{NO}$</td>
<td>$K_{NO,PAO}$</td>
<td>gN m$^{-3}$</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Saturation constant for $S_{PO4}$ (storage)</td>
<td>$K_{NO,PAO}$</td>
<td>gP m$^{-3}$</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Saturation constant for $S_{PO4}$ (growth)</td>
<td>$K_{NO,PAO}$</td>
<td>gP m$^{-3}$</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Saturation constant for $S_{HCO}$</td>
<td>$K_{NO,PAO}$</td>
<td>gN m$^{-3}$</td>
<td>0.05</td>
<td>0.05</td>
</tr>
</tbody>
</table>

**Stoichiometric parameters**

| Yield biomass/$X_{PHA}$ | $Y_{PHA}$ | gCOD gCOD$^{-1}$ | 0.625 | 0.6 |
| Yield biomass/$X_{TP}$  | $Y_{TP}$  | gCOD gCOD$^{-1}$ | 0.625 | 0.5 |
| Requirement of $S_{PO4}$ per $X_{TP}$ storage (P-storage) | $r_{PO4,TP}$ | gCOD gP$^{-1}$ | 0.2 | 0.2 |
| Requirement of $X_{TP}$ per $X_{PHA}$ storage (P-release) | $r_{PH}$ | gP gCOD$^{-1}$ | 0.4 | 0.35 |
| Production of $S_i$ in endog. biomass respiration | $f_{S_i}$ | gCOD gCOD$^{-1}$ | 0.1 | 0.2 |
| Production of $S_i$ in hydrolysis | $f_{S}$ | gCOD gCOD$^{-1}$ | 0 | 0 |
| Phosphorus content of $S_i$ | $r_{P}$ | gP gCOD$^{-1}$ | 0.01 | 0 |
| Phosphorus content of $S_{XG}$ | $r_{p,xi}$ | gP gCOD$^{-1}$ | 0 | 0 |
| Phosphorus content of $X_{TP}$ | $r_{p,x}$ | gP gCOD$^{-1}$ | 0.01 | 0.01 |
| Phosphorus content of $X_{XG}$ | $r_{P,XG}$ | gP gCOD$^{-1}$ | 0.01 | 0.005 |
| TSS to COD ratio for $X_i$ | $s_{TSS,xi}$ | g TSS / g X$_i$ | 0.75 | 0.75 |
| TSS to COD ratio for $S_{PO4}$ | $s_{TSS,PO4}$ | g TSS / g X$_{PO4}$ | 0.75 | 0.75 |
| TSS to COD ratio for $S_{XG}$ | $s_{TSS,XG}$ | g TSS / g X$_{XG}$ | 0.6 | 0.6 |
| TSS to COD ratio for biomass | $s_{TSS,BM}$ | g TSS / g BM | 0.9 | 0.9 |
| TSS to COD ratio for $X_{TP}$ | $s_{TSS,TP}$ | g TSS / g X$_{TP}$ | 3.23 | 3.23 |

**Kinetics**

Table 3 shows the kinetics of the EAWAG Bio-P module. The kinetic parameters used are listed in Table 4 for a temperature of 20°C together with their temperature coefficients $θ_T$. The following equation can be used to calculate the values for different temperatures $T$ (in °C): $k(T) = k(20°C) \times \exp(θ_T(T-20°C))$. The kinetic rate expressions for ASM3 are listed in Table 7.

**Kinetic and Stoichiometric Parameters**

All parameters from ASM3 (Table 8) are identical to the values for the calibrated version (Koch et al., 2000) except for the anoxic reduction factor for growth/storage of the heterotrophic organisms $η_{NO}$ which is set to 0.8 instead of 0.5. However, this is not a sensitive parameter for the mere ASM3 with only nitrogen removal (Koch et al., 1998). Saturation constants for $S_{PO4}$ ($K_{PO4,H} = K_{PO4,LA} = 0.01$) are introduced to take the phosphorus limitation into account. The calibration of the parameters of the EAWAG Bio-P module is presented in the second part of the paper.
PART TWO: CALIBRATION OF THE EAWAG BIO-P MODULE

The module was calibrated on the basis of measurements made within the scope of a project at the Neugut WWTP, Dübendorf and at a pilot plant in Tüffenwies, Zürich. This project investigated the possibilities and advantages of denitrification and EBPR in Switzerland and was completed in October 1999.

The whole model was implemented in AQUASIM 2.0_prerel3 for the simulation and the sensitivity analysis (Reichert, 1998).

PARAMETER CALIBRATION

An iterative approach was chosen to calibrate the complex model (ASM3 and Bio-P module) because it was essentially impossible to identify a single sensitive parameter from a single experiment. Highly correlated parameters were therefore calibrated in groups with different batch experiments and validated against the WWTP data. Only the most sensitive parameters were changed. The number of unidentifiable parameters was reduced by the simultaneous evaluation of multiple experiments (see Figure 1). For the simulation of the batch experiments an iterative procedure between plant and batch simulations was used to get the initial sludge characteristics. First a steady state run of the belonging plant and time was simulated and the sludge fractions and the parameters were taken from it and then the batch experiment was simulated. When the plant and the batch experiment could be modelled with the same parameter settings the iteration was finished.
The following experiments and measurements were selected to calibrate and validate the model:

A. Three batch experiments dealing with P-release and aerobic/anoxic P-uptake (Neugut WWTP and Tüffenwies pilot plant)
B. One series of batch experiments involving the wash-out and grow-in of PAO (Tüffenwies pilot plant)
C. Three weekly variations (Neugut WWTP)
D. Two diurnal variations (Tüffenwies pilot plant)
E. One long-term simulation of nine weeks (WWTP Neugut)

Moreover, three series of batch experiments for PAO decay (Figure 2) were carried out at the Tüffenwies pilot plant, but these were not modelled.

A listing of the experiments used for the calibration of each parameter is shown in Table 9.

**THEORETICAL DERIVATION AND LITERATURE**

$Y_{PAO,O2}$ and $Y_{PAO,NO}$: These parameters should initially be calculated from a theoretical point of view (Maurer, 1996) or taken from the literature (Smolders et al., 1994) on the basis of the heterotrophic yields from the calibrated ASM3 (Koch et al., 2000). The reduction of $Y_{PAO}$ compared to $Y_H$ depends on the substrate. For acetate a 15% reduction is calculated without taking into account the additional energy requirement for glycogen storage (Maurer, 1996). Smolders et al. (1994) measured a yield reduction of 13% for an EBPR organism culture compared to an aerobic culture fed with acetate. For propionate the reduction factor is decreased to 7% (Maurer, 1996). For the aerobic and anoxic yields of the PAO this results in:

\[
Y_{H,net,O2} = Y_{STO,O2} \cdot Y_H = 0.8 \cdot 0.8 = 0.64 \text{ g}\ X_H \text{ g SS}^{-1}
\]

(1)

\[
Y_{PAO,O2} = Y_{H,net,O2} \cdot 0.93 = 0.60 \text{ g}\ X_{PAO} \text{ g SS}^{-1}
\]

(2)

\[
Y_{H,net,NO} = Y_{STO,NO} \cdot Y_{H,NO} = 0.7 \cdot 0.65 = 0.455 \text{ g}\ X_H \text{ g SS}^{-1}
\]

(3)

\[
Y_{PAO,NO} = Y_{H,net,NO} \cdot 0.93 = 0.42 \text{ g}\ X_{PAO} \text{ g SS}^{-1}
\]

(4)

Since the nitrate data from the batch experiments could not be correctly modelled with this value, the anoxic yield of the PAO $Y_{PAO,NO}$ was increased to 0.5 gCOD gCOD$^{-1}$.

$Y_{PHA,O2}$ and $Y_{PHA,NO}$: These parameters can also be inferred from a theoretical viewpoint, but they could not be verified in the batch experiments either. Maurer (1996) calculated a value of 0.34 gCOD gP$^{-1}$ for $Y_{PHA,O2}$ and 0.5 gCOD gP$^{-1}$ for $Y_{PHA,NO}$. The default value for ASM2d of 0.2 gCOD gP$^{-1}$ had to be used for the Bio-P Module to simulate the batch experiments successfully. From an energetical point of view the calibration result is not correct. This could be due to an overestimation of the endogenous respiration on the basis of the decay experiments. The decay rate coefficient was derived from long-term experiments under starvation conditions and therefore a low PHA level adjusts. Moreover, under these experimental conditions a limitation by means of glycogen could play a crucial role. The decay rate was proportionally extrapolated to the entire PHA concentration range, which leads to a high endogenous respiration during periods of high PHA concentrations. This high anoxic endogenous respiration results in a high denitrification. To model the data (NOx and COD) correctly, $Y_{PHA}$ had to be adjusted.

iP: The phosphorus fractions $i_{PX}$ and $i_{PXS}$ could be calculated from modelled and measured wastewater and sludge characteristics with equation (5).

\[
\frac{i_{P,COD} \cdot X_{TSS}}{\text{measured}} \cdot \frac{i_{COD,TSS}}{\text{modelled}} \approx \frac{i_{PX1} \cdot X_1 + i_{PXS} \cdot X_S + i_{PBM} \cdot (X_H + X_{PAO} + X_A) + X_{PP}}{\text{measured}} \text{ (gP gCOD$^{-1}$)}
\]

(5)
The organic phosphorus content of the biomass $i_{PBM}$ was fixed at 0.014 gP gCOD$^{-1}$ as measured in the sludge from phases without EBPR.

**BATCH EXPERIMENTS**

*Series of batch experiments for PAO decay*

Batch experiments with sludge from the pilot plant in Tüffenwies were carried out to study the decay rates of polyphosphate and the endogenous respiration of PAO under aerobic and anaerobic conditions. Under the assumption that the polyphosphate pool is completely filled during the batch experiments, the decrease of PAO can be estimated. After stopping the inlet flow, sludge was taken from the anaerobic and aerobic compartments respectively. The maximum phosphorus uptake was determined in a batch experiment with the sludge from the anaerobic compartment. A similar experiment with the sludge from the aerobic compartment was used to find the maximum phosphorus release. These experiments were repeated after 48, 96 and 168 hours. More details can be taken from Siegrist *et al.* (1999).

The results (Figure 2) show that the polyphosphate content declines rapidly under aerobic conditions. This could be due to a lack of glycogen, which limits the P-release of the sludge from the aerated compartment. Therefore the results were verified with another series of batch experiments (see wash-out experiments without anaerobic zone). But the results give reliable hints, that the anaerobic decay can almost be neglected. The rate of the aerobic decay of polyphosphate ($b_{PP}$) is about 0.12 d$^{-1}$ at 15°C, which appears to be similar to the endogenous respiration rate of PAO. With a temperature coefficient $\theta_T$ of 0.07 °C$^{-1}$ (ASM2d) and the known temperature equation (Henze *et al.*, 2000), $b_{PP}$ becomes 0.2 d$^{-1}$ at 20°C. The experiments were carried out three times with similar results.

![Graph showing measured and simulated values for $S_{PO4}$, $S_{COD}$, and $S_{NOx}$](image)

Figure 3: Measured and simulated values for $S_{PO4}$, $S_{COD}$ ($S_s + S_i \cong$ filtered COD, assuming the influent is mainly acetate and the colloidal COD fraction is negligible due to adsorption onto flocs) and $S_{NOx}$ from a batch experiment in week 49 1997, Neugut WWTP. $C_{COD,ini}=4056$ gCOD m$^{-3}$, $S_{COD,ini}=12$ gCOD m$^{-3}$, best fit with $X_{PAO,ini}=404$ gCOD m$^{-3}$, $X_{PPini}=31.4$ gP m$^{-3}$. (Some lines are invisible because they lie one on top of the other).
**P-release and P-uptake**

Batch experiments to determine the maximum P-release as well as the maximum aerobic and anoxic P-uptake were carried out during all important phases of the project. Three experiments with sludge from different flow schemes and acetate as carbon source were selected for the calibration. The initial values of the sludge used for the batch experiments were calculated in a previous simulation of the plant, but also fitted in the range of ± 5%. The results shown in Figure 3 characterize a typical batch experiment.

The anaerobic phase (0-0.25 d) with phosphorus release was used to calibrate the three kinetic parameters $q_{PHA}$, $K_{SS,PAO}$, and $K_{PP,PAO}$ and the stoichiometric parameter $Y_{PO4}$. A sensitivity analysis showed that the three kinetic parameters are highly correlated and were therefore calibrated in parallel. Various batch experiments together with the series of batch experiments examining the grow-in and wash-out of PAO mentioned below reduced the number of unidentified parameters. As a stoichiometric parameter, $Y_{PO4}$ gives the ratio of phosphorus release to substrate uptake and depends on the substrate composition in the inlet. During the calibration, $Y_{PO4}$ was fitted with a mixed substrate source of wastewater and acetate. The value of 0.35 gP gCOD$^{-1}$ obtained differs slightly from the default value (0.4 gP gCOD$^{-1}$) in ASM2d (Henze et al., 2000) but is within the range of values found in the literature (e.g. Van Veldhuizen et al., 1999 (calib. model for wastewater): 0.36 gP gCOD$^{-1}$, Wild, 1997 (fermented primary sludge): 0.38 gP gCOD$^{-1}$, Kunst, 1991 (wastewater plus artificial substrates): 0.26 gP gCOD$^{-1}$) and is similar to the value used in a static model (Koch et al., 2001, 0.33 gP gCOD$^{-1}$).

The kinetic parameters $q_{PP}$, $K_{PHA}$, $K_{max,PAO}$ and $K_{iPP,PAO}$ were calibrated with the phosphorus uptake during the aerobic phase (experiment time 0.25-0.55 d). As in the anaerobic phase, these parameters show a high correlation. $K_{max,PAO}$ could also be confirmed with total phosphorus measurements. Johansson et al. (1996) state values between 0.1-0.4 gP gCOD$^{-1}$PAO. A typical mean value of 0.125 gP gCOD$^{-1}$PAO has been reported (Maurer, 1996). The calibration of the EAWAG Bio-P module led to a $K_{max,PAO}$ of 0.2 gP gCOD$^{-1}$PAO, which is equal to the value used by Brdjanovic et al. (1998). This $K_{max,PAO}$ value is also supported by Crocetti et al. (2000) who found a linear relation between the ratio of PAO per biomass and the sludge P-content based on 16S rRNA probes in enhanced cultures. Their P-contents are slightly higher than the values calibrated with the EAWAG Bio-P module for the Neugut WWTP and the Tüffenwies pilot plant, although this result could be interpreted as being due to the lab-scale environment without limitations. A $K_{max,PAO}$ value of 0.2 gP gCOD$^{-1}$PAO resulted from the calibration of the Bio-P module. But due to the selected $K_{iPP,PAO}$ value of 0.05 a typical polyphosphate content of about 0.12-0.15 gP gCOD$^{-1}$PAO was simulated. Figure 4 shows the stored polyphosphate per PAO depending on the SRT and the COD in the influent as simulated with the EAWAG Bio-P module for a full-scale plant (AAO scheme) by artificially varying the COD/P-inlet ratio.

![Figure 4: Effect of substrate availability for growth of the PAO calculated for different sludge retention times (SRT). Modelled with the EAWAG Bio-P module for a full-scale AAO system with artificial varied inlet data. $K_{max,PAO} = 0.2 \text{ gP gCOD}^{-1}$, $K_{iPP,PAO} = 0.05 \text{ gP gCOD}^{-1}$](image)
The reduction factors for the BPR processes (\(\eta_{\text{NO,PAO}}\), \(\eta_{\text{NO,end,PAO}}\), \(\eta_{\text{NO,sys,PP}}\), \(\eta_{\text{NO,resp,PHA}}\)) were calibrated with the results of parallel batch experiments with anoxic and aerobic phosphorus uptake. \(Y_{\text{PHA}}\) did not differ from ASM2d (Henze et al., 2000) and was set to 0.2 gCOD gP\(^{-1}\). The stoichiometric parameters \(Y_{\text{PHA,O2}}\), \(Y_{\text{PHA,NO}}\), \(Y_{\text{PAO,O2}}\) and \(Y_{\text{PAO,NO}}\) were first calculated from theoretical considerations as stated above, but the nitrate concentrations in the batch experiments could not be modelled with these values. A value of 0.5 gCOD gCOD\(^{-1}\) was found for \(Y_{\text{PAO,NO}}\). \(Y_{\text{PAO,O2}}\) was set to 0.6 gCOD gCOD\(^{-1}\) in contrast to the default value of 0.625 gCOD gCOD\(^{-1}\) of ASM2d.

**Batch experiments examining the grow-in and wash-out of PAO**

A series of batch experiments (Figure 5) with sludge from a pilot plant operated with and without anaerobic zone allowed the maximum decay (\(b_{\text{PP,PAO}}\)) and growth rate (\(\mu_{\text{PAO}}\)) to be calibrated. Furthermore, the P-release/P-uptake rates (\(q_{\text{PHA}}\), \(q_{\text{PP}}\)) from the batch experiments could be checked.

During a period of 140 d with different flow schemes and influent conditions, various batch experiments were carried out to examine the maximum phosphorus release. The first simulated phase (DEN_2, after an AAO phase) had a flow scheme with no anaerobic zone and a high artificial nitrate influent. The second and third phases had a UCT and an AAO flow scheme respectively. The batch experiments allowed the decay rates (DEN_2) and the maximum growth and storage rates (UCT_3, AAO_3) of the PAO in the plant to be estimated. Figure 5 shows the measured phosphorus release based on batch experiments and the modelled \(X_{\text{PP}}\) content. The decay rates were checked in the DEN_2 phase. The maximum growth and storage rates were calibrated in the UCT_3 and the AAO_3 phases.

The behaviour within the different phases shown in Figure 5 gives additional insight into the very sensitive ratio between the maximum rates \(\mu_{\text{PAO}}\), \(q_{\text{PHA}}\) and \(q_{\text{PP}}\), whereas the batch experiments dealing with the P-release and the aerobic/anoxic P-uptake provided indications for the saturation constants. The calibration showed that the maximum growth and storage rates on the one hand and the saturation constants on the other hand had all increased compared with the default values of ASM2d.

**Figure 5:** Simulated polyphosphate content and measured max. P-release in anaerobic batch experiments with sludge taken from Tüffenwies pilot plant (1997), operated without (0-42 d) and with an anaerobic zone (<0, 42-135 d). DEN: Pre-denitrification, AAO: EBPR flow scheme, UCT: EBPR flow scheme
PLANT DATA

The following chapter presents data only for phosphorus removal. The modelling of nitrogen removal and oxygen consumption is described in Koch et al. (2000). Average influent and effluent data together with some system information are shown in the appendix (Table 10).

Neugut WWTP

The experimental lane of the WWTP in Neugut, Duebendorf treats the wastewater of approximately 15,000 population equivalents (p.e.). It is modelled as a cascade of six CSTRs (Figure 6), which corresponds to data from a tracer experiment. The secondary clarifier is modelled with an inlet zone, a sludge blanket and a clear water zone. The volume of the sludge blanket was estimated from measured sludge-blanket heights and was calibrated with data from the last aerobic reactor, the effluent and the sludge recycle flow. This project examined and modelled AAO and UCT flow schemes. The phases selected here only show the results of periods with an AAO scheme.

![Figure 6: AAO scheme, Neugut WWTP (experimental lane), week 19/20 1996](image)

Table 5: Operating conditions of the Neugut WWTP (experimental lane), week 19/20 1996

<table>
<thead>
<tr>
<th>Reactor</th>
<th>Anaer1</th>
<th>Anaer2</th>
<th>Anoxic</th>
<th>Bivalent</th>
<th>Aerobic1</th>
<th>Aerobic2</th>
<th>C1</th>
<th>C2</th>
<th>Clear water zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume (m³)</td>
<td>348</td>
<td>348</td>
<td>454</td>
<td>454</td>
<td>787</td>
<td>635</td>
<td>100</td>
<td>100</td>
<td>1175</td>
</tr>
<tr>
<td>$S_{O_2,\text{sim}}$ (gO₂ m⁻³)</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>2.5-7.5</td>
<td>0.5-6.3</td>
<td>0.0-4.8</td>
<td>0.0-1.0</td>
<td>not meas.</td>
</tr>
</tbody>
</table>

Highly fluctuating oxygen concentrations in the aerobic2 compartment (between 0 and 6.5 gO₂ m⁻³) led to simultaneous denitrification there. However, the simulation of the P-uptake is not very accurate in this compartment because the oxygen data were recorded at a resolution of half an hour. To demonstrate that the model can predict the P-uptake efficiently, the measured and simulated data from the aerobic1 compartment are also shown.

Week 19/20 1996. In this week, the experimental lane was operated in AAO mode (Figure 6, Table 5) with an SRT (without the sludge blanket of the secondary clarifier) of approximately 12 d. During the simulated time period, the bivalent reactor was not aerated.

In this phase, an effect is shown which is often called the “Monday effect”. After periods with low COD loads in the influent, often after weekends, rainfall or public holidays, the phosphate load in the effluent is significantly increased on the following 1-2 d (Carucci et al., 1999). This effect is slightly underestimated in the simulation (Figure 7), probably as a result of the COD characterization of the influent. Usually only daily average samples were measured and the samples were combined with typical diurnal variations for the dynamic modelling. Moreover, fluctuating ratios of the readily degradable ($S_S$) to the total COD in the influent were determined with the help of a few respiration experiments. A constant ratio was selected for the simulation because no dynamic resolution for $S_S$ was available.
EAWAG Bio-P Module

In comparison to a simulation with ASM2d for the same time period (Carucci et al., 1999), the PHA pool is greatly increased and the P-uptake between the weekends could consequently be modelled more accurately. This is due to the increased maximum growth and storage rates as well as the increased saturation constants in comparison with the default values of ASM2d. This change allowed even the phosphate peaks in the effluent to be simulated after periods with a low COD load (the “Monday effect”).

![Graph showing phosphate and XPHA concentrations](image_url)

**Figure 7:** Simulated (lines) and measured on-line data (points) of phosphate and simulated XPHA concentrations in different compartments of the experimental lane, Neugut WWTP, week 19/20 1996

<table>
<thead>
<tr>
<th>Reactor</th>
<th>Anaer1</th>
<th>Anaer2</th>
<th>Anoxic</th>
<th>Bivalent</th>
<th>Aerobic1</th>
<th>Aerobic2</th>
<th>C1</th>
<th>C2</th>
<th>Clear water zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume [m³]</td>
<td>348</td>
<td>348</td>
<td>454</td>
<td>454</td>
<td>787</td>
<td>635</td>
<td>100</td>
<td>100</td>
<td>1175</td>
</tr>
<tr>
<td>$S_{O_2, sim}$ [gO₂ m⁻³]</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0-0.5</td>
<td>0.0-7</td>
<td>1.0-9.5</td>
<td>0.0-5.5</td>
<td>0.0-3.5</td>
<td>0.0-0.3</td>
<td>n. m.</td>
</tr>
</tbody>
</table>

**Table 6:** Operating conditions of the Neugut WWTP (experimental lane), week 11-19 1996

(C1: inlet channel, C2: sludge blanket)

*Long-term simulation.* In this period, the experimental lane was also operated in AAO mode (Figure 6, Table 6), with an average sludge retention time (exclusive the sludge blanket) of 12 d. The weekly variations indicated a decreasing polyphosphate concentration $X_{PP}$ toward the weekend. The long-term simulation shows that the model gives stable results over prolonged periods and that the decrease of $X_{PP}$ is attributed to the decreasing COD influent during the week (Figure 8).

The low resolution of the in reality highly fluctuating oxygen concentrations in the aerobic2 compartment led to reduced denitrification in the simulation as described for the weekly variation. Furthermore, it was later found that additional unwanted oxygen inputs occurred during this phase because of oxygen recycles between the aerobic and anoxic/bivalent zones and leakage from an air pipe into the anoxic compartment.
The results show good correspondence between the measured and the simulated P-release. The problems mentioned above caused an inadequate simulation of the P-uptake, but the range and dynamic behaviour are modelled in a satisfactory way.

Figure 8: Simulated (lines) and measured on-line data (points) of phosphate and simulated PHA concentrations in different compartments of the experimental lane, Neugut WWTP, weeks 11-19 1996

Figure 9: AAO scheme and operating conditions of the pilot plant in Tüffenwies, 29./30.01.1997
(C1: inlet area, C2: sludge blanket)

**Tüffenwies pilot plant**

The hydraulic behaviour of the pilot plant in Tüffenwies was defined via a tracer experiment. The activated sludge tanks can be modelled with a cascade of eight CSTRs and the secondary clarifier with an inlet area, a clear water zone and a sludge blanket. The simulation of a single diurnal variation requires an exact knowledge of the composition and conditions of the activated sludge. These initial conditions are very sensitive for modelling the behaviour of denitrification and Bio-P because of the strongly dynamic variation of the internal storage pools of polyphosphate and PHA. The polyphosphate pool varies between 2 and 10 daily P-loads. For the
simulation of the two diurnal variations, the initial conditions of the sludge were calculated from previous time periods of 100 d with daily averaged samples of the influent and an average oxygen supply in the aerated reactors. The modelling of a single diurnal variation with previous constant data has the advantage of accelerated computation, but may lead to an incorrect sludge composition at the beginning and therefore to inaccurate simulation data.

![Graphs showing simulated and measured concentrations of PO4-P, NH4-N, and NOx-N](image)

Figure 10: Simulated (lines) and measured (points) $S_{PO4}$, $S_{NH}$ and $S_{NO}$ concentrations in different compartments of the pilot plant in Tüffenwies, 29./30.01.1997 ($\mu_A = 1.6$ d$^{-1}$)

**Diurnal variation 29./30.01.1997.** During the 2 d with diurnal variation data, the pilot plant was operated in AAO mode (Figure 9) with an SRT of 12 d (without a sludge blanket).

All simulated values correspond well with the measured data (Figure 10). The initial nitrification rate was too low but could be fitted when the autotrophic growth rate ($\mu_A$) was increased to 1.6 d$^{-1}$. This value is comparable to the result of the ASM3 calibration of the Tüffenwies pilot plant ($\mu_A = 1.8$ d$^{-1}$) (Koch et al., 2000). The higher rate compared to Henze et al. (2000) is probably due to a high biofilm growth in the pilot plant. To simulate the correct denitrification rate, the anoxic reduction factor for growth and storage of the heterotrophic organisms ($\eta_{NO,H}$) was set to 0.8 instead of the 0.5 in the calibrated ASM3. $\eta_{NO,H} = 0.8$ is also the default value of ASM2d. In ASM3, where only the heterotrophic organisms handle the denitrification, the sensitivity of this parameter is very low, whereas with the Bio-P module the substrate competition between heterotrophic and phosphate accumulating organisms leads to a higher sensitivity. The increased reduction factor was used in all simulations described here with good results for the nitrogen predictions as well.
CONCLUSIONS

The *EAWAG Bio-P module* adds biological phosphorus removal to a calibrated version of ASM3. The calibrated ASM3 is extended by terms for phosphorus limitations in the growth processes of the biomass, but all processes and parameters, except for one, are the same. The processes of ASM2d were adapted to the endogenous respiration and some simplifications were made. The main differences are the omission of the fermentation process and the distinction between aerobic and anoxic growth yields. Moreover, the growth and decay processes for EBPR run at reduced rates under anoxic compared to aerobic conditions. The anaerobic decay was not taken into account. In contrast to other research results, the module is designed without an additional glycogen pool because previous research had shown no significant influence of glycogen on the EBPR processes in municipal wastewater under typical Swiss conditions. Biologically induced but inorganic calcium-phosphate precipitation is not yet included.

After a calibration procedure, ASM3 extended with the *EAWAG-Bio-P module* can predict the removal of nitrogen and phosphorus accurately. Different dynamic effects could be modelled, e.g. short-term effects such as the normal P-release and uptake, long-term effects such as the wash-out and grow-in of the PAO and even effluent PO₄-peaks after short periods with low COD loads (weekends, rainy days, holidays). It was possible to model all data with one set of default parameters. Only the autotrophic growth rate ($\mu_A$) had to be adapted to the particular operating and wastewater conditions. A maximum autotrophic growth rate ($\mu_A$) of 0.9-1.0 d⁻¹ was found at 20°C for the experimental lane of the large scale WWTP in Neugut, and in the simulation of the pilot plant in Tüffenwies this parameter was set to 1.6-1.8 d⁻¹ probably due to a high biofilm growth. In contrast to the calibrated version of the ASM3, the anoxic reduction factor for growth and storage of the heterotrophic organisms ($\eta_{NO,H}$) had to be set to 0.8 instead of 0.5.

There are several reasons for the deviations of the simulated results from the experimental data:

- The composition and condition of the sludge at the beginning of the simulation period can only be estimated. However, an exact knowledge of the initial PP and PHA-pool is crucial for the accurate modelling of EBPR and it is therefore inadequate to model only one diurnal variation. During a simulation period and data set of a week or more, the accuracy of the model improves due to better estimation of the sludge conditions.

- The PAO contain a PP and a PHA reservoir of several daily P and COD loads. These storage pools vary greatly. Only small changes in the internal storage pools could lead to significant variations of the simulated phosphate concentrations in the reactor in comparison to the measured values.

- Usually only daily average samples were measured and these were combined with typical diurnal variations for the dynamic modelling. Moreover, fluctuating ratios of the readily degradable ($S_5$) to the total COD in the influent were measured in a few respiration experiments (e.g. a day/night variation). A constant ratio was selected for the simulation because no dynamic measurements were available.

- The Bio-P module could only be validated with a high time and space resolution of COD, N and P and information about the internal storage products. In the project described here, the main values in the compartments were measured on-line but information about the internal storage pools (or at least the model components) was only available indirectly via simulation and parameter estimation. No reliable measurement methods for polyphosphate and glycogen were available so far.

It was advantageous for the calibration of highly correlating groups of parameters to combine different data sets such as batch experiments, series of batch experiments and plant data. In this work, a new model design was calibrated for the first time, but it is expected that the calibration expenditure could be reduced in future applications of the *EAWAG Bio-P module*. 81
ACKNOWLEDGEMENT

The authors wish to thank the operators of the Neugut WWTP, our analytical group and the numerous trainees and students who participated in this project.

APPENDIX

The average influent and effluent data together with some system information are given in Tables 7 - 10.

Table 7: Kinetic rate expressions for ASM3 (Henze et al., 2000)

<table>
<thead>
<tr>
<th>No.</th>
<th>Process</th>
<th>Process rate equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Hydrolysis</td>
<td>( k_h \frac{X_h}{X_h + X_s/X_h} X_h )</td>
</tr>
<tr>
<td>2</td>
<td>Aerobic storage of COD</td>
<td>( k_{STD} \frac{S_o}{K_{O,H} + S_o} \frac{S_h}{K_{S,H} + S_h} X_h )</td>
</tr>
<tr>
<td>3</td>
<td>Anoxic storage of COD</td>
<td>( k_{STD} \frac{S_NO}{K_{O,H} + S_NO} \frac{S_NO}{K_{S,H} + S_NO} \frac{S_h}{K_{S,H} + S_h} X_h )</td>
</tr>
<tr>
<td>4</td>
<td>Aerobic growth</td>
<td>( \mu_h \frac{S_o}{K_{O,H} + S_o} \frac{S_h}{K_{S,H} + S_h} \frac{S_{PO}}{K_{S,PO} + S_{PO}} \frac{S_{HCO}}{K_{S,HCO} + S_{HCO}} \frac{S_{NO}}{K_{S,NO} + S_{NO}} X_{STD} X_h )</td>
</tr>
<tr>
<td>5</td>
<td>Anoxic growth (deni)</td>
<td>( \mu_h \frac{S_NO}{K_{O,H} + S_NO} \frac{S_h}{K_{S,H} + S_h} \frac{S_{PO}}{K_{S,PO} + S_{PO}} \frac{S_{HCO}}{K_{S,HCO} + S_{HCO}} \frac{S_{NO}}{K_{S,NO} + S_{NO}} X_{STD} X_h )</td>
</tr>
<tr>
<td>6</td>
<td>Aerobic endog. resp.</td>
<td>( b_h \frac{S_o}{K_{O,H} + S_o} X_h )</td>
</tr>
<tr>
<td>7</td>
<td>Anoxic endog. resp.</td>
<td>( b_h \frac{S_NO}{K_{O,H} + S_NO} \frac{S_h}{K_{S,H} + S_h} X_{STD} )</td>
</tr>
<tr>
<td>8</td>
<td>Aerobic resp. of ( X_{STD} )</td>
<td>( b_h \frac{S_o}{K_{O,H} + S_o} X_{STD} )</td>
</tr>
<tr>
<td>9</td>
<td>Anoxic resp. of ( X_{STD} )</td>
<td>( b_h \frac{S_NO}{K_{O,H} + S_NO} \frac{S_h}{K_{S,H} + S_h} X_{STD} )</td>
</tr>
<tr>
<td>10</td>
<td>Nitrification</td>
<td>( \mu_A \frac{S_A}{K_{O,A} + S_A} \frac{S_{NO}}{K_{A,NO} + S_{NO}} \frac{S_{PO}}{K_{A,PO} + S_{PO}} \frac{S_{HCO}}{K_{A,HCO} + S_{HCO}} \frac{S_{NO}}{K_{S,NO} + S_{NO}} X_A )</td>
</tr>
<tr>
<td>11</td>
<td>Aerobic endog. resp.</td>
<td>( b_A \frac{S_A}{K_{O,A} + S_A} X_A )</td>
</tr>
<tr>
<td>12</td>
<td>Anoxic endog. resp.</td>
<td>( b_A \frac{S_{NO}}{K_{O,A} + S_{NO}} \frac{S_{NO}}{K_{A,NO} + S_{NO}} X_A )</td>
</tr>
</tbody>
</table>
Table 8: Calibrated kinetic and stoichiometric parameters for ASM3 (Koch et al., 2000) at T=20°C with exponential temperature dependence θ_T (after slash). Values differing from the IAWQ default values are shown in bold print.

<table>
<thead>
<tr>
<th>Kinetic parameters</th>
<th>Symbol</th>
<th>Unit</th>
<th>Default value ASM3</th>
<th>ASM3 calib.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrolysis rate constant</td>
<td>k_H</td>
<td>d⁻¹</td>
<td>3.0/0.04</td>
<td>9.0/0.04</td>
</tr>
<tr>
<td>Hydrolysis saturation constant</td>
<td>K_S</td>
<td>-</td>
<td>1.0</td>
<td>1.0</td>
</tr>
</tbody>
</table>

*Heterotrophic organisms X_H*

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Unit</th>
<th>Default ASM3</th>
<th>ASM3 calib.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aerobic storage rate constant</td>
<td>k_STO</td>
<td>d⁻¹</td>
<td>5.0/0.07</td>
<td>12.5/0.07</td>
</tr>
<tr>
<td>Saturation/inhibition constant for S_O,H</td>
<td>K_O,H</td>
<td>gO₂ m⁻³</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Saturation constant for substrate S_STO</td>
<td>K_STO</td>
<td>gCOD m⁻³</td>
<td>2.0</td>
<td>10.0</td>
</tr>
<tr>
<td>Max. aerobic growth rate of X_H</td>
<td>µ_H</td>
<td>d⁻¹</td>
<td>2.0/0.07</td>
<td>3.0/0.07</td>
</tr>
<tr>
<td>Saturation constant for S_NO,H</td>
<td>K_NO,H</td>
<td>gN m⁻³</td>
<td>0.6</td>
<td>0.8</td>
</tr>
<tr>
<td>Max. endogenous respiration rate of X_H</td>
<td>b_H</td>
<td>d⁻¹</td>
<td>0.2/0.07</td>
<td>0.3/0.07</td>
</tr>
<tr>
<td>Anoxic reduction factor for endog. respiration</td>
<td>η_NO,end,H</td>
<td>-</td>
<td>0.5</td>
<td>0.33</td>
</tr>
</tbody>
</table>

*Autotrophic organisms X_A*

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Unit</th>
<th>Default ASM3</th>
<th>ASM3 calib.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. aerobic growth rate of X_A</td>
<td>µ_A</td>
<td>d⁻¹</td>
<td>1.0/0.105</td>
<td>0.9-1.8/0.105</td>
</tr>
<tr>
<td>Saturation constant for S_O,A</td>
<td>K_O,A</td>
<td>gO₂ m⁻³</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Saturation constant for S_NO,A</td>
<td>K_NO,A</td>
<td>gN m⁻³</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Anoxic yield growth X_H on X_STO</td>
<td>Y_H,O2</td>
<td>gCOD gCOD⁻¹</td>
<td>0.63</td>
<td>0.80</td>
</tr>
<tr>
<td>Yield growth X_H on X_STO</td>
<td>Y_H</td>
<td>gCOD gCOD⁻¹</td>
<td>0.54</td>
<td>0.65</td>
</tr>
<tr>
<td>Nitrogen content of S_NO</td>
<td>s_NO</td>
<td>gN gCOD⁻¹</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Nitrogen content of X_H</td>
<td>s_H</td>
<td>gN gCOD⁻¹</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>Nitrogen content of X_A</td>
<td>s_A</td>
<td>gN gCOD⁻¹</td>
<td>0.04</td>
<td>0.03</td>
</tr>
<tr>
<td>Nitrogen content of biomass (X_H and X_A)</td>
<td>s_BM</td>
<td>gN gCOD⁻¹</td>
<td>0.07</td>
<td>0.07</td>
</tr>
</tbody>
</table>

*Heterotrophic and autotrophic organisms (X_H, X_A)*

| Production of X_I in endog. biomass respiration | f_XI | gCOD gCOD⁻¹ | 0.20 | 0.20 |
| Yield of stored products per S_O | Y_STO,O2 | gCOD gCOD⁻¹ | 0.85 | 0.80 |
| Anoxic yield of stored products per S_O | Y_STO,O2 | gCOD gCOD⁻¹ | 0.80 | 0.70 |
| Aerobic yield growth X_H on X_STO | Y_H,O2 | gCOD gCOD⁻¹ | 0.63 | 0.80 |
| Anoxic yield growth X_H on X_STO | Y_H | gCOD gCOD⁻¹ | 0.54 | 0.65 |

*Stoichiometric parameters*

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Unit</th>
<th>Default ASM3</th>
<th>ASM3 calib.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen content of S_I</td>
<td>s_I</td>
<td>gN gCOD⁻¹</td>
<td>0.01</td>
</tr>
<tr>
<td>Nitrogen content of X_I</td>
<td>s_I</td>
<td>gN gCOD⁻¹</td>
<td>0.03</td>
</tr>
<tr>
<td>Nitrogen content of X_S</td>
<td>s_S</td>
<td>gN gCOD⁻¹</td>
<td>0.02</td>
</tr>
<tr>
<td>Nitrogen content of X_S</td>
<td>s_S</td>
<td>gN gCOD⁻¹</td>
<td>0.04</td>
</tr>
<tr>
<td>Nitrogen content of biomass (X_H and X_A)</td>
<td>s_BM</td>
<td>gN gCOD⁻¹</td>
<td>0.07</td>
</tr>
</tbody>
</table>

*Changed during the calibration of the Bio-P module.*
**Table 9: Experiments for estimating kinetic and stoichiometric parameters for the EAWAG Bio-P module**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Unit</th>
<th>Estimated from</th>
<th>Second source</th>
</tr>
</thead>
<tbody>
<tr>
<td>(b_{PP})</td>
<td>(d^{-1})</td>
<td>Batch series &quot;decay of (X_P)&quot;</td>
<td></td>
</tr>
<tr>
<td>(q_{PHA})</td>
<td>(d^{-1})</td>
<td>Batch series &quot;grow-in of PAO&quot;</td>
<td></td>
</tr>
<tr>
<td>(\mu_{PAO})</td>
<td>(d^{-1})</td>
<td>Batch series &quot;wash-out of PAO&quot;</td>
<td></td>
</tr>
<tr>
<td>(K_{SS,PAO})</td>
<td>(gCOD\ m^{-3})</td>
<td>Batch experiment P-release</td>
<td></td>
</tr>
<tr>
<td>(K_{PP,PAO})</td>
<td>(gP\ gCOD^{-1})</td>
<td>Batch experiment P-release</td>
<td></td>
</tr>
<tr>
<td>(Y_{PAO})</td>
<td>(gP\ gCOD^{-1})</td>
<td>Literature</td>
<td></td>
</tr>
<tr>
<td>(\eta_{NO,PAO})</td>
<td>-</td>
<td>Batch experiment aer./anox. P-uptake</td>
<td></td>
</tr>
<tr>
<td>(\eta_{NO,end,PAO})</td>
<td>-</td>
<td>Indirectly from (S_{NO}) respiration in batch experiments</td>
<td></td>
</tr>
<tr>
<td>(\eta_{NO,lys,PP})</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\eta_{NO,resp,PHA})</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(i_{PSI})</td>
<td>(gP\ gThOD^{-1})</td>
<td>Batch experiments P-uptake</td>
<td></td>
</tr>
<tr>
<td>(i_{PCOD,C})</td>
<td>(gP\ gCOD^{-1})</td>
<td>Batch experiments P-uptake</td>
<td></td>
</tr>
<tr>
<td>(i_{PXI})</td>
<td>(gP\ gThOD^{-1})</td>
<td>Batch experiments P-release</td>
<td></td>
</tr>
<tr>
<td>(K_{PO4,PAO})</td>
<td>(gP\ m^{-3})</td>
<td>Literature</td>
<td></td>
</tr>
<tr>
<td>(K_{PO4,PP})</td>
<td>(gP\ m^{-3})</td>
<td>Literature</td>
<td></td>
</tr>
<tr>
<td>(Y_{PHA})</td>
<td>(gCOD\ gP^{-1})</td>
<td>Batch experiments P-uptake</td>
<td></td>
</tr>
<tr>
<td>(Y_{PO4})</td>
<td>(gP\ gCOD^{-1})</td>
<td>Batch experiments P-release</td>
<td></td>
</tr>
<tr>
<td>(K_{O,PAO})</td>
<td>(gO2\ m^{-3})</td>
<td>Plant data</td>
<td></td>
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<tr>
<td>(K_{NO,PAO})</td>
<td>(gN\ m^{-3})</td>
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<td></td>
</tr>
<tr>
<td>(K_{NH,PAO})</td>
<td>(gN\ m^{-3})</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(K_{HCO,PAO})</td>
<td>(mol\ m^{-3})</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(b_{PHA})</td>
<td>(d^{-1})</td>
<td>Theoretically derived on basis of calibrated (Y_{PAO})</td>
<td></td>
</tr>
</tbody>
</table>

**Table 10: Average influent and effluent data together with some system information**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>(C_{COD,0})</td>
<td>250 gCOD m^{-3}</td>
<td>350 gCOD m^{-3}</td>
<td>380 gCOD m^{-3}</td>
</tr>
<tr>
<td>(C_C)</td>
<td>21.4 gN m^{-3}</td>
<td>23.9 gN m^{-3}</td>
<td>36.7 gN m^{-3}</td>
</tr>
<tr>
<td>(C_P)</td>
<td>4.14 gP m^{-3}</td>
<td>6.0 gP m^{-3}</td>
<td>10.1 gP m^{-3}</td>
</tr>
<tr>
<td>(S_t)</td>
<td>10 %</td>
<td>10 %</td>
<td>10 %</td>
</tr>
<tr>
<td>(S_{SO})</td>
<td>4 %</td>
<td>4 %</td>
<td>4 %</td>
</tr>
<tr>
<td>(X_S)</td>
<td>53.3 %</td>
<td>53.3 %</td>
<td>53.3 %</td>
</tr>
<tr>
<td>(X_I)</td>
<td>20 %</td>
<td>20 %</td>
<td>20 %</td>
</tr>
<tr>
<td>(X_H)</td>
<td>11.9 %</td>
<td>11.9 %</td>
<td>11.9 %</td>
</tr>
<tr>
<td>(X_{TO})</td>
<td>0.1 %</td>
<td>0.1 %</td>
<td>0.1 %</td>
</tr>
<tr>
<td>(X_{PAO})</td>
<td>0.2 %</td>
<td>0.2 %</td>
<td>0.2 %</td>
</tr>
<tr>
<td>(X_{PHA})</td>
<td>0.1 %</td>
<td>0.1 %</td>
<td>0.1 %</td>
</tr>
<tr>
<td>(X_A)</td>
<td>0.4 %</td>
<td>0.4 %</td>
<td>0.4 %</td>
</tr>
<tr>
<td>Last aerated tank</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TSS</td>
<td>2.2 kg m^{-3}</td>
<td>2.2 kg m^{-3}</td>
<td>2.4 kg m^{-3}</td>
</tr>
<tr>
<td>(i_{F,COD})</td>
<td>0.03 gP gCOD^{-1}</td>
<td>0.024 gP gCOD^{-1}</td>
<td>0.029 gP gCOD^{-1}</td>
</tr>
<tr>
<td>(i_{S,COD})</td>
<td>0.07 gN gCOD^{-1}</td>
<td>0.065 gN gCOD^{-1}</td>
<td>0.065 gN gCOD^{-1}</td>
</tr>
<tr>
<td>(S_{SO})</td>
<td>1.5 gN m^{-3}</td>
<td>1.35 gN m^{-3}</td>
<td>0.4 gN m^{-3}</td>
</tr>
<tr>
<td>(S_O)</td>
<td>2.5 gN m^{-3}</td>
<td>2.6 gN m^{-3}</td>
<td>8.9 gN m^{-3}</td>
</tr>
<tr>
<td>Discharges</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Q_{e})</td>
<td>3860 m^{3} d^{-1}</td>
<td>3860 m^{3} d^{-1}</td>
<td>1.9 m^{3} d^{-1}</td>
</tr>
<tr>
<td>(Q_{es})</td>
<td>5800 m^{3} d^{-1}</td>
<td>5800 m^{3} d^{-1}</td>
<td>2.1 m^{3} d^{-1}</td>
</tr>
<tr>
<td>(Q_{n})</td>
<td>8600 m^{3} d^{-1}</td>
<td>8600 m^{3} d^{-1}</td>
<td>4.46 m^{3} d^{-1}</td>
</tr>
<tr>
<td>(Q_{ps})</td>
<td>290 m^{3} d^{-1}</td>
<td>250 m^{3} d^{-1}</td>
<td>0.07 m^{3} d^{-1}</td>
</tr>
</tbody>
</table>
REFERENCES


CHAPTER 6

MODELLING OF AERATION SYSTEMS AT WASTEWATER TREATMENT PLANTS

Leiv Rieger, Willi Gujer and Hansruedi Siegrist

Manuscript in preparation
Modelling of Aeration Systems at Wastewater Treatment Plants

ABSTRACT

A model for the response time of aeration systems at WWTPs is proposed. It includes the delays caused by the air supply system, the rise time of the air bubbles and all control loops except the master DO controller. Different approaches for model calibration are required depending on the available data for the airflow as well as the loading and process conditions. The model can be used for simulation studies which compare different types of controllers under conditions close to reality.

INTRODUCTION

The air supply system is the major factor in energy costs, accounting for some 60% of total energy consumption. The biological processes depend significantly on the presence or absence of a certain amount of DO in the reactors. The aeration control systems at WWTPs must therefore operate correctly and reliably in order to ensure optimal results in terms of economic and environmental viability. The design and parameterization of the control loops also remains a problem at WWTPs. The main uncertainties are due to the unknown time constants of the system. There are many static design rules which give a first hint as to the parameter settings but they are unsuitable for predicting the dynamic behaviour under different loading or process conditions. A suitable tool which takes the time constants explicitly into account is dynamic simulation. This type of modelling allows better controller design than a purely empirical evaluation and has the following advantages:

- Systematic and time-saving evaluation of different control concepts under conditions close to reality
- Evaluation under different loading and process conditions
- Comparison of control concepts under exactly the same conditions
- Tuning of slow control loops

The goal of this paper is to propose a simple model of the delay caused by the air supply system and a method of calibrating the model based on step-change experiments. Three case studies will demonstrate the applicability of the model.

AERATION SYSTEM

From a control engineering perspective, the aeration system of a WWTP can be divided up into four parts (Figure 1):

A.) Controlled system (reactor with influent, effluent and the associated biological, chemical and transport processes)
B.) Measuring equipment (DO sensor)
C.) Final controlling equipment (air supply system)
D.) Controller (DO control loop)

In this paper, the goal is to model the DO control system according to the requirements of a process engineer. This means that a control loop should be evaluated in order to optimize the biological processes. The following models are required to describe the aeration control system (Figure 2):
Aeration System Model

- Reactor model:
  - Respiration (biokinetic models, e.g. ASM family, Henze et al., 2000)
  - Influent model (calculation of model components based on measurements)
  - Hydraulic behaviour and transport processes
  - Aeration process
- Sensors (see Rieger et al., 2003a)
- DO and other controllers
- Air supply system

Figure 1: Typical action diagram of a control loop used in control engineering (DIN 19226-4, 1994)

Figure 2: Action diagram of a control loop as proposed in this work

The control of the air supply system consists of various control loops according to the plant design. The inner or machine control loop regulates the blower unit, which contains special ramps for starting up or driving down the machines or special switching orders for the engines. Root-type blowers are controlled to operate at a fixed capacity, whereas turbo-type blowers have a feedback controller which controls the measured airflow rate at the calculated set-point. The next loop controls the capacity of the blower unit. This is normally done by a pressure controller in the air collector system, a DO control loop (by using the average DO concentration over all lanes) or by means of additional information such as valve positions (valve-position control). The control loop of each individual lane regulates the air supply to that specific lane.

MODELLING

Dynamic simulation is a suitable tool for combining the various parts of the measuring and control system and taking the time constants explicitly into account. The required complexity of the aeration system model depends on the goal of the study. Most studies focus on comparisons of different process strategies which require no detailed models. However, studies designed to compare different controllers under conditions close to reality or to parameterize controllers offline need strict differentiation between the models for the controller, reactor, sensor and aeration system.

The aeration system as proposed in this work (Figure 2) includes the air supply system, all control loops except the master DO control loop (see next paragraph) and an additional delay caused by the rise time of the air bubbles and resistances of the diffusers. The air supply system consists of various control equipment such as the set of blowers and includes frequency converters (actuators) and valves (final controlling elements), air pipes and collectors. It differs from that shown in Figure 1, where the final controlling element is part of the controlled system. This is because strict differentiation between the processes in the reactor and the air supply is required to test a control loop under changing load and process conditions.

DEFINITION OF THE MASTER CONTROLLER

The first simplification step is to define the master controller which is responsible for the air supply to the reactor (Figure 2). The study normally limits itself to the DO controller of only one lane. The basic assumption is that all lanes receive the same load and have the same oxygen
respiration. What has to be modelled depends on the type of DO control applied. If the air pressure in the collector is controlled, the important control loop is the DO controller of the individual lane, since the air supply is controlled only by the valves of the lanes. If the air supply is controlled by the average DO concentration of all lanes, the master control loop is the blower controller and the valve controller is used only for fine-tuning the air distribution.

As a result, the aeration system will be simplified to one control loop and a delay of the remaining controllers, which is added to the response time of the air supply system (Figure 2).

**RISE TIME OF AIR BUBBLES / RESISTANCE OF DIFFUSERS**

The complete gas exchange should normally be integrated in the aeration process. But because the residence time of the air bubbles in the reactor and its delay is commonly neglected, we suggest including it within the aeration system model. This delay is in the range of 0.1 – 1 min. The rise velocity of an air bubble is ca. 30 cm/sec for common bubble diameters of 2 -3 mm (Figure 3). For a reactor with a depth of 4 m this would result in a rise time of ca. 15 sec.

![Figure 3: Rise velocity of an air bubble depending on the bubble diameter (Siegrist, 2004)](image)

Because the airflow measurement – which is used for calibration - is located in front of the diffusers, this delay must also be estimated or off-gas measurements must be carried out.

**AERATION SYSTEM MODEL**

The aeration system is modelled as a delay in the alteration of the airflow into the reactor. The real-time behaviour is typically a combination of a more or less constant delay due to resistances in pipes and throttles and the velocity of the rising air bubbles in the reactor and a dynamic part caused by the acceleration or shutdown of the blower unit.

To characterize the dynamic behaviour, we suggest using the same terms as those used to characterize the on-line sensors (ISO 15839, 2003; Rieger *et al*., 2003a). On the basis of a step response, the delay (or dead time) is defined as the time needed to reach 10% of the final value of a step response (\(T_{10}\)). The overall time needed to reach 90% of the final value of the step response is introduced as the response time (\(T_{90}\)).

In the SIMULINK implementation, the response time of the airflow rate is transformed by a linear transfer function. The time behaviour is modelled using a series of Laplace transfer functions (eq. 1). The number of first-order transfer functions in series (n) determines the ratio of the delay (\(T_{10}\)) to the response time (\(T_{90}\)). With respect to the required simulation time, the number of transfer functions in series should be as low as possible. This kind of modelling results in a constant delay which does not depend on the size of the step change. The dynamic part is neglected for reasons of simplification.

\[
g_{\text{Aer. system}}(s) = \frac{1}{(1 + T\cdot s)^n} \quad [\text{eq. 1}]\]  

\(G_{\text{Aer. system}}\) = transfer function for response time  
\(T = T_{90}/\text{factor}\) = time constant to achieve a defined \(T_{90}\) time for a given \(n\)  
\(s = \text{Laplace operator}, n = \text{number of transfer functions in series}\)
MODEL CALIBRATION

A problem which often occurs when calibrating the model is the absence of a measuring device for the airflow in each individual lane. This prevents direct calibration on the basis of airflow measurements. An indirect method is to fit the modelled DO concentrations to the measured values by introducing a response time of the airflow rate. In this case, however, the oxygen transfer rate must be known, since the parameters for the oxygen transfer and the response time of the aeration system model are not clearly identifiable.

Depending on the available data, we propose three approaches for the calibration of the aeration system model based on step-change experiments of the airflow (Figure 5):

1) Calibration based on airflow measurements and estimation of air bubble rise time and delay due to the resistance of the diffusers.

2) Calibration of the oxygen gas transfer in a first step and calibration of the response time of the air supply in a second step.

   2a) If a calibrated biokinetic model with sufficient information about the load and process conditions during the period of the step-change experiment is available (normally the data set used for the simulation study), the aeration system model should be calibrated using the complete plant model.

   2b) In the case that no information about the influent is available (e.g., for first design purposes), we suggest the use of the following simplified model which takes measurements only for ammonia and DO into account.

Simplified calibration model

The basic assumption is that the respiration at the steady state before a step-change experiment is equal to the oxygen transfer rate, and the limitations encountered during the experiment depend only on the ammonia and DO concentrations. The simplified model has to be calibrated to the second steady state, which will be reached after the step-change experiment, by tuning two Monod constants.

Figure 4 shows the suggested system for calibrating the aeration system model. The sensor model is needed to differentiate between the response time of the sensor and the aeration system. The definition of the sensor models can be found in Rieger et al. (2003a). Simplified models for the oxygen transfer and the respiration are proposed in the following section.

Model for oxygen transfer rate

The oxygen transfer rate (OTR) is modelled according to eqs. 2 and 3.

\[
\alpha K_{L,a,20} = \alpha \frac{\text{OU}_{20} \cdot h_{\text{aer}} \cdot Q_{\text{air}}}{S_{O_{S},\text{Sat},20} \cdot V_{\text{BB}}} \quad [\text{d}^{-1}] \quad [\text{eq. 2}]
\]

where:
- \(\alpha K_{L,a,20}\) = Oxygen mass transfer coefficient under operating conditions at 20°C [d⁻¹]
- \(\text{OU}_{20}\) = Oxygen utilization at 20°C and \(S_O = 0\ mg/l\ [g/(m^3\cdot m)]\)
- \(\alpha\) = Coefficient for ratio of activated sludge to clear water conditions [-]
- \(S_{O,\text{Sat},20}\) = DO saturation concentration at 20°C [g/m³]
- \(h_{\text{aer}}\) = Immersion depth of the air [m]
- \(V_{\text{BB}}\) = Reactor volume [m³]
- \(Q_{\text{air}}\) = Airflow rate at normalized cond. (T=273.15°K, p=101325Pa) [Nm³/d]
Aeration System Model

**Simplified model for respiration**

The changes in the limitations due to DO and ammonia concentrations after the step change are modelled with two Monod terms. The unlimited respiration is firstly calculated taking the initial conditions for DO and ammonia into account (eq. 4). Then the limited respiration is calculated on the basis of the measured ammonia and the modelled DO concentration (eq. 5). The Monod constants may differ from the commonly used values (e.g. Henze *et al.*, 2000) because they include all the oxygen-consuming processes and not only the nitrification. Figure 6 shows the SIMULINK implementation.

\[
\text{resp} = \frac{\text{resp}_{\text{max}}}{\text{OR}_{\text{ini}} + \frac{S_{\text{O}_2}}{K_{\text{O}}} + \frac{S_{\text{NH}_3}}{K_{\text{NH}}}}
\]

[eq. 4]

where:
- \(\text{resp}_{\text{max}}\) = Unlimited respiration rate \([\text{g}/(\text{m}^3 \cdot \text{d})]\)
- \(\text{OR}_{\text{ini}}\) = Oxygen transfer rate at steady state before the step change \([\text{g}/(\text{m}^3 \cdot \text{d})]\)
- \(S_{\text{O}_2}/S_{\text{O}}\) = Actual/initial DO concentration \([\text{g}/\text{m}^3]\)
- \(S_{\text{NH}_3}/S_{\text{NH}}\) = Actual/initial ammonia concentration \([\text{g}/\text{m}^3]\)
- \(K_{\text{O}}\) = Saturation constant for \(S_{\text{O}_2}\) \([\text{g} \text{O}_2/\text{m}^3]\)
- \(K_{\text{NH}}\) = Saturation constant for \(S_{\text{NH}_3}\) \([\text{gN}/\text{m}^3]\)

\[
\text{resp}_{\text{actual}} = \text{resp}_{\text{max}} \left( \frac{S_{\text{O}_2}}{K_{\text{O}} + S_{\text{O}}} \cdot \frac{S_{\text{NH}_3}}{K_{\text{NH}} + S_{\text{NH}}} \right)
\]

[eq. 5]

**EXPERIMENTS**

Depending on the kind of DO controller used, one of the following experiments must be carried out to obtain the required data independently of the controller and as an input for the model calibration:

- **Air-pressure controlled blower unit**: Step-change experiment run by switching between two valve positions (the pressure control has to operate satisfactorily without influencing the DO control loop).
- **DO controlled blower unit**: Step-change experiment of the airflow rate (including start or stop of additional blower according to normal operation rules).

**CASE STUDIES**

The experiments were carried out at the full-scale WWTPs Thunersee and Werdhoelzli and at the EAWAG pilot plant. The DO control loop of WWTP Thunersee controls the air supply of two parallel reactors by using the average DO concentration. The EAWAG pilot plant has one blower.
Aeration System Model

for each reactor. WWTP Werdhoelzli has a pressure control loop for the blower set and a second loop to control the DO concentration by changing the valve openings of the individual lanes. To calibrate the aeration system models, a model for the used DO sensor must be integrated. The response times of the sensors were evaluated according to ISO 15839 (2003).

Unfortunately, no detailed influent measurements are available for the periods of the step-change experiments. A full-scale validation consequently remains a task for the future.

WWTP THUNERSEE

At WWTP Thunersee, approach 2b) was used for the calibration of the aeration system model. The reactor models (Figure 2) were calibrated on the basis of data from an intensive measuring campaign of 10 d. The measured DO concentrations and the airflow rate of the blower unit (calculated from the measured capacity of the blower unit) were used to calibrate the oxygen transfer. Figure 7 shows the calibration results for the airflow rate of the first aerated reactor.

![Figure 7: Modelled and calculated airflow in reactor aer1. WWTP Thunersee Nov. 2000](image)

The same parameters for the oxygen transfer were used in step-change experiments to calibrate the aeration system model. The simplified model was used because no additional intensive measuring campaign was carried out. The response time of the DO sensors were tested at $T_{90} = 1.1$ min with one transfer function (Figure 8). The step-change experiments of the air supply resulted in a response time ($T_{90}$) of the aeration system of 4 min with five transfer functions in series (Figure 9).

![Figure 8: Step-change experiment to evaluate the response time of the DO probe used](image)

![Figure 9: Modelled step-change experiment of airflow rate (above) and measured and modelled DO concentration (without/with response time of aeration system, below) WWTP Thunersee. NH$_4$-N = const. = 0.1 mg/l. Best results with $T_{90} = 4$ min and five transfer functions in series.](image)
WWTP WERDHOELZLI

At WWTP Werdhoelzli, the airflow rate of the lane under evaluation is measured, thus allowing direct calibration of the response time of the air supply system (approach 1). To validate the model, the DO concentration was also modelled according to approach 2b. The oxygen transfer calibration was performed on the basis of routine plant data (Rieger and Siegrist, 2003b). The DO concentrations were modelled by using the simplified model because no detailed influent measurements were available. The response time of the DO probe was estimated as 1 min (from information supplied by the manufacturer: \(T_{90} = 22\) sec plus the adjusted attenuation as 40 sec). In addition to the delay of the airflow, an estimated delay of 1 min for the rising gas bubbles and the diffusers was added. The airflow delay is \(T_{90} = 3.2\) min, and thus very short, but it would be even shorter if the air pressure was constant during the step change (Figure 11). It can be assumed that the drop will be smaller during normal operation. The total response time of the aeration system amounts to 4.2 min.

![Figure 10: Modelled and measured step change of airflow rate (above) and DO concentration (below, without delay, with delay of airflow and with the entire response time of the aeration system) WWTP Werdhoelzli. Best results for reaching measured airflow rate with \(T_{90} = 3.2\) min and four transfer functions in series. Best result for reaching the measured DO concentration with an additional delay of \(T_{90} = 1\) min and six transfer functions.](image)

![Figure 11: Measured drop of air pressure during start-up of the step-change experiment](image)

EA WAG PILOT PLANT

The airflow rate is also measured at the EA WAG pilot plant. Figure 14 shows the modelled and calibrated airflow rate which was calibrated according to approach 1. To calibrate the oxygen transfer, the DO concentration was modelled using the measured airflow rate (Figure 13). The response time of the DO probe (measured intentionally with an old membrane and an attenuation of 1 min) amounts to \(T_{90} = 4\) min with two transfer functions in series (Figure 12). The rise time of the air bubbles and the delay due to the resistance of the diffusers were neglected (reactor height 2 m). The DO concentrations were modelled by using the simplified model (approach 2b) as no detailed influent measurements were available.
The response time ($T_{90}$) for the aeration system of the EAWAG pilot plant amounts to 4.3 min. Eight transfer functions in series were necessary to model the delay. The rather high response time and especially the dead time for this direct blower-reactor combination are due to the intermittent operation of the blowers. The concept was implemented to run the blowers above a minimum permitted capacity. The fraction of aeration time within a switching cycle of two minutes is calculated on the basis of the demands of the DO control loop. The dead time cannot be modelled completely because of the simplified modelling of the DO controller without intermittent aeration.

To validate the model, a step-change experiment of the DO set point was carried out (Figure 15). A PI controller is modelled with the real parameter settings. Although the model cannot predict the DO concentration exactly, it can be clearly seen that without the delays (dotted line) the system behaviour differs significantly from the measured behaviour. The differences between modelled and measured data are due to the simplified controller used and the load conditions, which were not taken into account (only a constant load was assumed). A differential algorithm is applied in reality whereas a continuous PI controller is used in the simplified model. Moreover, the real controller is subject to additional acceleration rules to decrease the response time (full aeration after increase of DO set point, no aeration after decrease).
CONCLUSIONS

Detailed modelling of the air supply system is needed if the goal of the simulation study is to design, compare or evaluate different types of DO controllers under conditions close to reality. Maximum demands are made on the model accuracy if DO controllers are parameterized offline. To test the controller behaviour under varying load and process conditions, it is necessary to differentiate between the time constants of the air supply system, the DO controller, the DO sensor, the oxygen gas transfer and the biological and chemical processes.

In this work, different types of aeration systems are analysed and modelled on the basis of step-change experiments. The first step of model simplification is to define the DO control loop, which is responsible for supplying the correct amount of air to the reactor. It depends on the kind of controller used for the air supply. The aeration system is modelled as a response time of the air supply system, the remaining control loops and the rise time of the air bubbles. A further simplification is to model the delay independently of the size of the step change.

Three calibration methods for the aeration system model are proposed depending on the availability of airflow measurements and influent data.

- Direct calibration on airflow measurements and estimation of rise time of air bubbles
- Calibration of oxygen transfer as a first step, calibration of aeration system model as the second step
  - with detailed information about the loading situation, the complete plant model is used
  - without information about the loading situation, a simplified model is proposed

The calibration is problematic only on the basis of DO measurements, because the oxygen utilization (OU20, α) and the response time (T90) of the aeration model are not clearly identifiable. So it is a precondition for the calibration on the basis of DO measurements that the parameters for the oxygen gas transfer are known.

The results from three different plants show that the response times of the aeration systems are in the range of 4-5 min. Taking all processes and time constants into account, some 30 min are needed to reach a new steady state after a step change of the airflow rate. With an air-pressure control loop for the regulation of the blower unit, the air supply seems to be somewhat faster, but problems in keeping the pressure at the defined level precluded a shorter response time in this special case. Moreover, the control by the average DO concentration is less favourable, since both the control loops for the blower unit and the individual lane are based on the same DO measurements. During the optimization of these controllers, the time constants of the two control loops play an important role and must be adapted in order to prevent oscillating systems.

Future effort is necessary to validate the models within the scope of a detailed simulation study and under different load and process conditions. The step-change experiments should be part of the measuring campaign. If more calibrated applications of the aeration system model are available, it should be possible to develop a classification system for design purposes similar to that existing for on-line sensors (Rieger et al., 2003a).

REFERENCES


CHAPTER 7

SOCIO-ECONOMIC ASPECTS
Socio-Economic Aspects

INTRODUCTION

This chapter focuses on some socio-economic aspects of optimization measures and especially on the implementation of measuring and control systems. A chain of incentives extending from the Swiss Agency for the Environment, Forests and Landscape (SAEFL) down to the plant operators is proposed and the interests and measures of the stakeholders involved are discussed. Special problems occurring during the design and implementation of the measuring and control systems are analysed in a second part. Although this work relates to Swiss conditions, its main results are equally applicable to other industrialized countries.

INCENTIVES

Why do control systems not work properly? Our studies indicate that the reason is a lack of incentives to deal with the greatly varying interests and demands of the stakeholders involved at all levels of urban water management. Without effective incentives, the sustained application of a control concept is jeopardised. The major stakeholders together with their authorities with respect to WWTP operation are listed in Figure 1. The scheme reflects the situation of larger plants which make a distinction between political leadership, the plant manager and the operator-in-chief. At smaller plants, these stakeholders are often merged into one unit. To show the general chain of incentives and to simplify the figure, it is drawn only in top-down mode, but there are obviously many more connections in both directions. A detailed analysis of the processes used in the field of wastewater treatment with the stakeholders involved is given in Binggeli (2003).

![Figure 1: Stakeholders in the wastewater treatment process with their authorities](image-url)
Table 1 gives a detailed analysis of the interests and incentives of the stakeholders.

<table>
<thead>
<tr>
<th>Stakeholder</th>
<th>Interests and objectives</th>
<th>Incentives and measures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Swiss Agency for the Environment, Forests and Landscape (SAEFL)</td>
<td>• Near natural water bodies • Proper wastewater drainage and treatment • No relocation of pollutants • Optimised mass fluxes</td>
<td>• Federal laws and regulations for water protection (GSchG, 1991; GSchV, 1998; StoV, 1986) • Subsidy • Guidelines • Studies (e.g. nitrogen elimination in CH)</td>
</tr>
<tr>
<td>Cantonal agencies for the environment</td>
<td>• Implementation of Federal laws • Observance of regulations and technical standards • Minimised effort for surveillance</td>
<td>• Cantonal laws and regulations (e.g. effluent load tax) • Surveillance of WWTPs • Subsidy • Studies and benchmarking to show optimization potentials</td>
</tr>
<tr>
<td>Political leadership (Local politicians, plant commission, ...)</td>
<td>• Low operation costs (advantage of location) • Cost-covering plant operation • Compliance with laws • Compliance with budget • Prevention of bad publicity</td>
<td>• Budget planning • Employment of plant manager • Guidelines for plant operation • Wastewater fees</td>
</tr>
<tr>
<td>Plant manager</td>
<td>• Compliance with budget and laws • Well-operating plant • Prestige • Decision-making authority • Enough resources • Innovative technology</td>
<td>• Definition of concrete objectives for the plant (e.g. optimization goals) • System of incentives for operators • Definition of salaries</td>
</tr>
<tr>
<td>Operator-in-chief</td>
<td>• Compliance with requirements for effluent limits and purification efficiency • Proper plant operation</td>
<td>• Definition of concrete objectives for the operators • Evaluation of operators according to objectives</td>
</tr>
<tr>
<td>Operators</td>
<td>• Adequate salary • Acknowledgement and status • Regular work schedule</td>
<td>• Feedback to evaluation and general plant operation</td>
</tr>
</tbody>
</table>

**SWISS AGENCY FOR THE ENVIRONMENT, FORESTS AND LANDSCAPE**

The Federal agency supports the definition of the general objectives for the environment and is responsible for implementing the Federal laws and regulations (GSchG, 1991; GSchV, 1998; StoV, 1986). Whether these laws give sufficient incentives for plant optimization will not be discussed in this work.

The relevant Federal regulation (GSchV, 1998) defines the effluent concentration limits and purification efficiency, e.g. for nitrogen and phosphorus, as follows:

- **Ammonia** = \(< 2 \text{ mg N/l (in a 24-h composite sample)} \) and elimination efficiency > 90% (for sensitive rivers and temperature > 10°C)
- **Total nitrogen** = As much removal as possible if no specific demands are made
- **Total phosphorus** = \(< 0.8 \text{ mg P/l (annual mean value)} \) and elimination efficiency > 80% (for lakes and sensitive rivers)

The SAEFL may subsidize special projects or optimization measures of international significance (defined in GSchG, 1991). However, the general shortfalls in public budgets mean that the importance of subsidies is decreasing.
CANTONAL AGENCIES FOR THE ENVIRONMENT

In Switzerland, the Federal laws have to be substantiated by cantonal laws or regulations (e.g. KGSchG, 1996 of the canton of Berne). The cantonal agencies have the duty of controlling the observance of the regulations and technical standards. Due to their limited budgets, it is in their interest to minimise this monitoring effort.

The experience gained in a project designed to apply innovative aeration control concepts indicates that the cantons should improve incentives for optimising plant operation. The following points can increase the acceptance of optimization measures:

Feedback: The feedback on the monitoring data from the cantonal agencies differs between the cantons. In our experience, giving detailed feedback leads to increased acceptance of the monitoring measurements and improves plant operation. In some cantons, the control measurements and self-surveillance data are analysed and evaluated by the cantonal agency and a detailed annual report is written for the plant. Good practice is to include a personal discussion in the supervision process.

As part of the feedback, the canton should provide information for assessing the efficiency of the plant and give hints on general optimization potentials. This can be done by benchmarking (organised by the canton) or specific studies (e.g. the study by the cantons of Berne and Solothurn about control of flow measurements, Kaufmann and Volkart, 2001).

Evaluation of monitoring data: A detailed analysis and evaluation of the cantonal control measurements in combination with self-surveillance by the plant would represent a good instrument for increasing the accuracy of the plant data. Budgetary constraints are often given as a reason for the limited number of cantonal measurements and the restricted data analysis. Thomann (2003) showed how the increase in utilisable information for detecting systematic errors depends on the number of cantonal control measurements. Thus if only four cantonal measurements (which is a common number) are carried out, an error in the $\text{BOD}_5$ influent measurements can only be identified (on a significance level of 5%) if it exceeds 40%. With eight measurements, an error can be detected in the range between 10 to 20% (Thomann, 2003).

Example: In the canton of Luzern, all WWTPs have to send their monitoring data to a cantonal database which calculates various indexes after performing basic plausibility checks. The indexes (e.g. for SRT, energy consumption, gas production, operating costs, etc.) are used for benchmarking and to reveal the optimization potentials of the individual plant. The results are sent to the plant in an annual report and may be discussed in a personnel meeting. The data evaluation of the canton of Basel-Landschaft is particularly forward-looking. Various mass balances are automatically calculated within the cantonal database.

Effluent load tax: At cantonal level, an effluent load tax could be defined which – in our experience – offers the best incentives for plant optimizations. However, only two Swiss cantons have introduced an effluent load tax in their water quality regulations. The cantons of Berne and Solothurn impose this tax for the following compounds (KGSchG, 1996):

- $\text{NH}_4\text{-N} = 4 \, \text{CHF/kg N effluent}$
- $\text{NO}_3\text{-N} = 1 \, \text{CHF/kg N effluent}$
- $\text{PO}_4\text{-P} = 30 \, \text{CHF/kg P effluent}$
- $\text{COD} = 0.70 \, \text{CHF/kg COD effluent}$
- $\text{Discharge} = 0.05 \, \text{CHF/m}^3 \, \text{effluent}$

Without an effluent load tax, optimization of the aeration control – which is the main topic of this work – can be financed only by the savings achieved by reducing energy or chemicals consumption. If an effluent load tax is imposed, the improvements to the environment are evaluated on a monetary basis and are therefore included in the cost calculations. A cost-benefit calculation would even give a positive result, although the reduction potential for energy consumption alone is probably insufficient.
Socio-economic Aspects

The principle of an effluent load tax appeals to the personal responsibility of the plant operators and is not based on a cost-intensive policy of bans, regulations and sanctions. An evaluation of the effluent load tax of the canton of Berne can be found in GSA (2001).

**Political Leadership**

The political leadership consists mainly of the local politicians and the plant commission, who are responsible for defining the objectives of the individual WWTP. They are under pressure from the cantonal agencies (laws and regulations), the citizens (elections) and the industry (job offers and taxes). Their duty is to guarantee compliance with the laws and regulations and to check that the plant operates according to the budget.

The combination of the effluent load tax and the demand for cost-covering wastewater fees (GSchG, 1991) represents an incentive for the political leadership to insist on plant optimization in order to obtain a location advantage. Cost-covering operation also allows a real cost-benefit analysis.

The political leadership is often overstretched by the complex processes of a WWTP. They often cannot be expected to give a reasonable and well-balanced answer to the technical and environmental problems which occur. We would therefore suggest that external advice be periodically or permanently obtained, for instance from an independent ‘plant engineer’.

**Plant Manager**

The plant manager is responsible for personnel management as well as the financial aspects. His brief is to maintain expenditures within the defined budget and to keep the plant running. He must define concrete objectives and tasks for his plant.

A major part of his task is to reduce the variable costs. Depending on the existence of an effluent load tax, these costs consist mainly of this tax in addition to energy consumption, P-precipitants and sludge disposal (personnel costs are only variable if positions can be reduced). Since only two Swiss cantons impose an effluent load tax, the optimization measures have to be financed mainly from reductions in energy and chemicals consumption and sludge disposal. With respect to aeration control the energy consumption is of major importance.

To motivate his operators, the plant manager should apply a system of incentives based on an evaluation of whether the operators have reached defined goals. The incentives may take the form of financial contributions (salary) or acknowledgements (rating, honouring).

**Operator-in-Chief**

The operator-in-chief has to pass on the incentives defined by the plant manager and formulate concrete tasks for the operators. His goal is to operate the plant below the effluent limits, to ensure its purification efficiency and keep it running without technical problems.

A system of incentives for the operator-in-chief could take the following form: he would have to perform a list of tasks which are monitored and newly defined by the plant manager, for instance once a year. His salary would then depend on the successful performance of his operational goals. An example of a specific operational goal might be to reduce the nitrogen load by 20%.

**Example:** A negative example would be if rating the operator-in-chief (by the canton or the plant manager) leads to the wrong decisions. Thus, if we take only the effluent concentrations for ammonia and phosphorus into account but not the total nitrogen concentration and the energy
and chemical consumption, the operator will have a strong incentive to keep the effluent concentrations well below the limits. To prevent a violation of the effluent limit, he will apply a high dose of P-precipitants and aerate more than necessary.

During the implementation of new aeration control systems, it is important to create effective incentives for the plant staff. The extra work performed by the operators in maintaining and monitoring the sensors as well as testing the control system and reacting to any errors must be acknowledged.

Example: Without effective incentives the following situation can occur: If the implementation is a success, the plant manager will earn praise for the reduced costs, but the operators merely have more work to do. If it goes wrong, the operator-in-chief will be held to account because he is responsible for the effluent limits.

Besides a system of incentives, it is also important to specify clear responsibilities and decision-making authority for the different tasks. Thus the maintenance of the measuring devices should be the responsibility of a designated operator (preferably someone with lab experience) and his representative. At smaller WWTPs, maintenance of the devices is often integrated in the changing weekly duty schedule of the laboratory. In this case out-sourcing of the measurements could be a solution. However, this is still the future in the field of urban water management.

**Operators**

To ensure a sustained and adaptable application of the control loops, it is essential to integrate the operators from the outset and to inform them of at least the basic background of the process control. Problems arise if these systems are given low priority by the plant staff due to inadequate incentives, the overwhelming pressure of daily business as well as a lack of understanding of the processes involved.

If the optimization goals are not clearly communicated to the operators they will not see the need for them. So it is important to set them clear targets (e.g. x mg/l or kWh/d) which should be achieved by means of a specific optimization measure. Thus the goal of ammonia-based aeration control is to reduce the energy consumption and the total nitrogen discharge. For Swiss conditions subject only to effluent limits for ammonia and not for total nitrogen, such an optimization is normally not a response to a violation of effluent limits. Moreover, the plants typically had no problems running only DO-based aeration control systems.

Example: If the operators are not involved in the optimization process, a newcomer to the plant (the external engineer) will tell them that their previous work was wrong. In addition, many new instruments will be installed in the plant and the new aeration control system will mean that the plant will run close to the effluent limits, at least for ammonia. Minor wrong decisions could then cause serious violations of the effluent limits.

From the point of view of the operator, it is important not only to reduce costs but also to ensure stable and robust plant operation as well as to minimize the effort needed to maintain the newly installed system. It should be kept in mind that unstable plant operation would have serious cost consequences for overall performance due to the violation of effluent limits and increased personnel effort.

**Operator training:** Because the application of advanced control concepts increases the demands on the knowledge of the operators, their training should be extended by lessons on control concepts and measuring equipment. The danger of violations of the effluent limits as a result of the control measures should also be discussed.
DESIGN AND IMPLEMENTATION OF MEASURING AND CONTROL SYSTEMS

Many technical problems could be prevented if the planning process were improved. The following section looks at practical experience.

INTERACTION BETWEEN SPECIALISTS

The design of measurement and control systems for wastewater treatment plants is often not a synchronous process of selection of a process scheme, measurement equipment and controller design. Instead, it can still be observed that these tasks are carried out separately without sufficient interaction. This is partly due to a lack of interdisciplinary knowledge by the experts involved and partly to an insufficient time frame for the planning phase. This often leads to sub-optimal operation of the measurement and control systems.

A good way of preventing omissions in the planning phase is to set up a planning group consisting of the plant manager, the operator-in-chief, a member of the plant commission, a process engineer and a control engineer. Additionally, an independent process engineer should be asked to evaluate the results. A software engineer will also discuss the implementation with the planning group and will program the control system.

Dynamic simulation represents a suitable tool for integrating the knowledge of all the experts involved and ensuring an easily-understood exchange of information. The process engineer provides the biological and hydraulic models to describe the controlled system (Figure 4) with great accuracy. The control engineer defines the controller model and an expert in measuring equipment provides information about specific sensors.

CONTROLLER DESIGN

A first step during the implementation of a controller is to select the right control algorithm. In the wastewater business, this selection is often not the task of a control engineer. Instead, the process engineer defines it on the basis of his own experience or pre-determined guidelines. A problem may arise if the notation specifies a type of controller which is unsuitable for the control task. Figure 2 and Figure 3 show typical notations for control algorithms at WWTPs. The flowchart suggests an I-controller, but this could be sub-optimal due to its high susceptibility to oscillations. The notation is often applied by process engineers, probably because it reflects their kind of thinking. The controller characteristic in Figure 3 leads to the implementation of a P-controller. If a PI-controller were to be the best choice, as is the normal case for aeration control, for instance, it is almost impossible to show this on a flowchart. The control or software engineer who is responsible for the implementation will naturally perform his programming according to the specifications.

![Figure 2: Program flowchart of an I-controller (Alex et al., 2004)](image1)

![Figure 3: Characteristic of a P-controller (Alex et al., 2004)](image2)
To integrate the control engineer’s knowledge, a notation should be used which leaves the selection of a suitable controller open. Figure 4 shows an action diagram of the kind commonly used by control engineers. In this diagram, the type of controller may be pre-defined or left open.

**Figure 4: Action diagram of a control loop (according to DIN 19226-4, 1994)**

**DOCUMENTATION AND CONTROL OF SUCCESS**

Good documentation is the basis for the sustainable and long-lasting operation of a measuring and control system. The required adaptations to changes in influent load or other conditions can only be made with a predictable effort if all information about the system is available. However, in reality a well-documented system tends to be an exception.

An important step during the implementation of measuring and control systems is the control of their success. It should be performed by the operator-in-chief with the help of the process and control engineer. A concept or protocol has to be defined in advance in order to test and fine-tune the controllers. Besides the control target, the requirements on the control authority and the test methods (e.g. step changes) have to be selected. If the success control is left to the operators during normal operation, they will be overstretched.

*Example: If the parameterization is left to the operators, they will tune the behaviour of the control system according to their experience. The control system would then probably operate in line with the behaviour of the system manually controlled by the operator, and this is not always the best choice.*

**CONCLUSION**

Experience of socio-economic aspects was gained from a project which involved five WWTPs, four cantons and two federal agencies (Swiss Agency for the Environment, Forests and Landscape and the Swiss Federal Office of Energy). The analysis and evaluation of the project indicates a lack of incentives to deal with the greatly varying interests and demands on optimizations extending from the national environment agency to the plant staff. Major potentials for improvements were identified at cantonal level and in the motivation of the operators for carrying out optimization measures.

At cantonal level, the most effective incentive was found to be an effluent load tax. It has a beneficial effect on plant optimizations because the improvements in the environment are evaluated on a monetary basis and therefore form part of the cost calculations. Another improvement would be to enhance the cantonal feedback to the WWTP. Although major restrictions exist due to limited budgets, we feel that the benefits of a more accurate database and additional optimization measures will exceed the extra effort required.
At plant level, a system of incentives should be introduced to motivate the operators to perform the optimization measures. This can be done by financial contributions or acknowledgements. If no effective incentive for the plant staff exists, the optimization will not give the best possible result or will fail after the experts have left the plant. Besides the incentives, it is important to specify clearly defined responsibilities on the one hand and grant sufficient decision-making authority on the other.

The second part of this chapter investigates the design and implementation process. Problems were identified in the interaction between the specialists involved and in a lack of sufficient documentation and success monitoring.

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CHAPTER 8

CASE STUDIES
Case Studies

INTRODUCTION

During the present work, extensive measuring campaigns, simulation studies and full-scale implementations of aeration-control concepts were carried out on different WWTPs. The aim was to increase the nitrogen elimination in parallel with a reduction of the energy consumption and to use existing capacities for biological phosphorus removal (Bio-P), at least temporarily. As a minimum, these concepts should be applicable to existing plants designed for nitrification.

All three WWTPs under evaluation are conventional activated-sludge plants with fixed volumes for pre-denitrification and nitrification and cover a range of plant sizes from 35,000 population equivalents (p.e.), 130,000 p.e. up to 600,000 p.e. This should guarantee the applicability of the study to other plants.

PROCEDURE

The scheme shown in Figure 1 is used for the case studies. The goals have to be defined together with the plant manager and the operator-in-chief. The data quality evaluation should begin directly after the start-up of the optimization study and should accompany all the measuring campaigns. The simulation study provides the basis for selecting the optimal control concept or for enhancing the plant. In the full-scale implementations of this work, more than one control concept was tested on each occasion. The optimal controller settings have to be determined after adaptations to the specific plant or modifications due to first results. Finally, the success must be monitored on the basis of a cost-benefit calculation. All steps have to be documented in detail and should also be comprehensible to people not directly involved in the study.

DEFINITION OF GOALS

The goals of the studies were to increase the nitrogen elimination in parallel with a reduction of the energy consumption. The constraints were to keep the effluent concentrations below the specified regulation limits. The ammonia limit of 2 mg N/l in the 24-h composite sample was the main factor restricting the aeration control. If enough free capacity exists in the plant, it should be used for biological phosphorus removal (Bio-P) to reduce the dosage of P-precipitants and the costs of sludge disposal. Special emphasis should be placed on the implementation of the measuring and control system. The system must continue to run even when the specialist has left the plant. This requires understandable and adaptable control concepts, suitable sensors with low maintenance requirements and tools for monitoring the measuring devices.

Figure 1: Scheme of an optimization study
DATA QUALITY EVALUATION AND CONTROL

Good data quality is essential for reliable results as well as for the design of efficiently operating control systems. Figure 2 proposes a concept for the evaluation and control of the data quality in optimization studies. The first step of data evaluation should be to analyse existing data and locate gaps in routine measurements. A few additional measurements will allow mass balances to be calculated on the basis of redundant information. The combination of different mass balances allows systematic measuring errors to be identified, located and quantified (Thomann, 2003). Additional experiments are required to obtain values for the precision of the equipment and analytical methods and to evaluate the response times of the measuring devices (Rieger et al., 2003a) and the actuators (Chapter 6). The intensive measuring campaign for the simulation study should not start until the mass balances can be closed. During this campaign, redundant information must be measured to allow quality checks on this data set too. Thomann (2003) describes a method of mass balancing designed especially for short data sets. The implementation and success monitoring should be accompanied by additional measurements, but their frequency can be reduced in comparison to the simulation data set.

**Phases**

1.) Routine data collection and first data evaluation

- **Collection of plant routine data**
  - Operational data (SRT, hydraulics, set points, dosage of precipitants and digester supern.,...)
  - Plant layout (Process scheme, lanes,...)
  - Performance data (In-/effluent/reactor conc., flow rates)

- **First data evaluation** (Evaluation of gaps in routine data and first data reliability checks)

2.) Data quality assurance

- **Closing gaps in routine data** (Additional routine measurements to enable data quality assurance)
  - Quality of routine data (Mass balances, reliability checks,...)
  - Validation experiments (Validation of detected potential errors. E.g. accuracy of lab and flow measurements,...)
  - Special experiments (Characterization of measuring devices and actuators,...)

3.) Data quality monitoring for simulation study, implementation and control of success

- **Measuring campaign for simulation study**
  - Data quality evaluation (Is accuracy adequate for objectives?)

- **Accompanying measurements during implementation and control of success**
  - Data quality evaluation (Is accuracy adequate for objectives?)

Figure 2: Concept for evaluating and monitoring the data quality

**CONTROLLER DESIGN**

The control goal is to keep the ammonia concentration at the end of the aerated zone near a defined set-point. This is done by increasing or decreasing the amount of air which is blown into the reactor. Due to the Monod dependence, the modelled nitrification rate reaches ca. 80% of the maximum at DO concentrations of 2 mg/l (depending on the half saturation constant, which is
Case Studies

normally 0.5 mg/l). The ammonia control loop is consequently above the conventional DO control loop. This guarantees DO concentrations below a limit of 2-3 mg O$_2$/l, even if the ammonia is above the set-point. Below an ammonia set-point, the oxygen input will be decreased and capacity for an enhanced denitrification arises in parallel with a reduction in energy consumption.

Whether the oxygen input can be switched off completely or only reduced to a minimum depends on the kind of aeration system used. If ceramic aerators are used, a minimum air flow rate has to be ensured, whereas membrane aerators can normally deal with the situation that the air supply is completely switched off.

Since the ammonia sensor is installed at the end of the aerobic zone (feed-back concept), the signal may be too late for peak loading. At plants with a highly dynamic influent combined with plug flow behaviour and small reactor volumes, this can lead to violation of the effluent limits. This effect is increased if sensors with a high response time (> 30 min.) are used (Alex et al., 2003). One solution is to combine feed-back and feed-forward concepts. An additional ammonia sensor gives the required time reserve to prepare the plant for a peak load.

The evaluated aeration control concepts enhance the existing DO control loop (Figure 3) by an ammonia control loop. The following basic concepts have been tested:

- On-off control of the blowers based on the ammonia concentration (Figure 4)
- DO set-point adjustment based on the ammonia concentration (Figure 5)
- Combination of feed-back and feed-forward control using a maximum condition (Figure 6).

**Figure 3: DO control loop**

**Figure 4: DO control loop + ammonia on-off control**

**Figure 5: DO + ammonia control loops**

**Figure 6: DO + ammonia feed-forward/feedback control**

**SIMULATION STUDIES**

The plant models were calibrated and validated on the basis of intensive measuring campaigns at WWTP Morgental and WWTP Thunersee. In addition, the hydraulic behaviour of the plants was...
evaluated by means of tracer experiments using sodium bromide. For WWTP Werdhoelzli, an artificial data set was created by analysing the available routine data and some diurnal variations. The simulation studies were carried out to evaluate the potential of the plants and to design, test and finally select the best controller for each specific plant.

The simulation study at WWTP Thunersee was based on the existing effluent load tax of the canton of Berne, whereas a fictitious effluent load tax is used for the studies at WWTP Morgental and WWTP Werdhoelzli, where no official tax exists.

**Effluent quality tax in the canton of Bern (KGSchG, 1996):**

- $\text{NH}_4\text{-N} = 4 \text{ CHF/kg N}$
- $\text{NO}_3\text{-N} = 1 \text{ CHF/kg N}$
- $\text{PO}_4\text{-P} = 30 \text{ CHF/kg P}$

**Effluent quality tax (fictitious):**

- $\text{NH}_4\text{-N} = 1 \text{ CHF/kg N} \text{ (for concentrations < 2 mg N/l)}$
- $\text{NH}_4\text{-N} = 4 \text{ CHF/kg N} \text{ (for concentrations > 2 mg N/l)}$
- $\text{NO}_3\text{-N} = 1 \text{ CHF/kg N}$
- $\text{PO}_4\text{-P} = 30 \text{ CHF/kg P}$

The energy costs were calculated on the basis of 0.15 CHF/ kWh. The costs of the phosphorus precipitants were set to 3 CHF/kg P precipitated and the costs for the precipitation sludge disposal to 7 CHF/kg P.

**FULL-SCALE IMPLEMENTATIONS**

On the basis of the simulation studies, the selected control concepts were adapted to several constraints of the plants and implemented on a full scale at WWTP Morgental and WWTP Thunersee. Measuring campaigns were carried out to validate the simulation results. At WWTP Werdhoelzli, the control concepts are being discussed and will be applied in the near future.

Since no additional mixing devices were installed in the normally aerated zones, the sludge settled during phases without aeration.
CASE STUDIES

Case studies were carried out for WWTP Morgental and WWTP Thunersee. For WWTP Werdhoelzli, further enhancements are still under discussion but will be based on two simulation studies on ammonia control and the implementation of the AI-process scheme carried out during this work.

WWTP WERDHOELZLI

WWTP Werdhoelzli treats the wastewater from the city of Zurich and several nearby villages. Because a second WWTP in Zurich (WWTP Glatt) failed to satisfy the effluent standards, its operation was stopped in 2002 and its wastewater was also connected to WWTP Werdhoelzli. With a current capacity of some 550,000 p.e., WWTP Werdhoelzli is the largest treatment plant in Switzerland and must eliminate substantial quantities of nitrogen because the receiving river Limmat flows into the Rhine. The plant was initially designed for nitrification only. In 1997 two anoxic compartments comprising 28% of the total volume were implemented in each of the twelve aeration tanks (Figure 7). This allowed 55-60% of the nitrogen to be removed (Siegrist et al., 2000). In December 2001 a storage tank for concentrated de-icing wastewater (average concentration about 50 g TOC/l) from Zurich airport was installed. The de-icing water is transported by trucks from the airport to the storage tank and then dosed into the influent of the activated sludge system. More details on the simulation studies and further process optimizations can be found in Siegrist et al., 2004, Rieger and Siegrist, 2003b and Rieger and Siegrist, 2003c.

![Process scheme WWTP Werdhoelzli (one of twelve lanes)](image)

**Goal definition**

To further improve nitrogen removal and reduce aeration energy, WWTP Werdhoelzli co-financed a research project for improving aeration control by introducing in-line ammonium sensors (Rieger and Siegrist, 2003b). A second goal of the study was to evaluate the application of enhanced biological phosphorus removal together with reduced air supply.

**Data quality**

Since only a relative comparison is to be made, no data quality control was carried out. The artificial weekly variation is based on an evaluation of the routine measurements of the plant laboratory of the years 2000 and 2001 and eleven measured diurnal variations.

**Simulation study**

A simulation study for WWTP Werdhoelzli was carried out to compare the costs of the aeration energy, the phosphate precipitation and a fictitious effluent quality tax for different aeration control concepts. An important cost factor is the reduction of the phosphate precipitants and the sludge production due to enhanced biological phosphate removal (Bio-P). The ASM3 with the
Case Studies

EAWAG Bio-P module (Rieger et al., 2001) was selected as the biological process model. The aeration system was modelled according to Alex et al. (2002) including the energy consumption of the blower unit. Only a basic calibration of the biological model was carried out. The energy consumption and amount of air used were calibrated with the mean values from a six-month data set with daily average samples.

Table 1: Modelled control versions at 15°C with parameter settings (Rieger and Siegrist, 2003b)

<table>
<thead>
<tr>
<th>No</th>
<th>Control concept</th>
<th>Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>V0</td>
<td>Actual control version</td>
<td>DO set-point = 2 mg/l, return sludge = 25,000 m³/d (1 lane)</td>
</tr>
<tr>
<td>V1</td>
<td>DO set-point control based on NH₄,ext at the end of the aeration tank (NH₄ feed-back control)</td>
<td>NH₄,ext &gt; 1.8 mg/l =&gt; DO set-point = 2 mg/l; NH₄,ext &lt; 1.6 mg/l =&gt; min. air flow = 0.7 m³/(h * aerator), valve of last aeration register minimum 70% open</td>
</tr>
<tr>
<td>V1a</td>
<td>V1 + control of valve for last aeration register based on DO at the end of aerated zone</td>
<td>According to V1 + possible reduction of valve opening to minimum 10% to reach minimal air flow</td>
</tr>
<tr>
<td>V2</td>
<td>DO set-point control based on combination of NH₄ feed-back and feed-forward control</td>
<td>According to V1a + feed-forward control based on an NH₄ sensor in the primary effluent (Eq. 1 and 2)</td>
</tr>
<tr>
<td>V3</td>
<td>Feed-forward control of digester supernatant (DS) dosage</td>
<td>According to V1a + control of DS dosage based on the ammonium load in the primary effluent</td>
</tr>
<tr>
<td>V3a</td>
<td>Separate treatment of digester supernatant</td>
<td>According to V1a + separate treatment of digester supernatant</td>
</tr>
</tbody>
</table>

On the basis of an additional ammonia sensor in the effluent of the primary clarifier and a flow measurement, the feed-forward control calculates the time when full aeration is necessary. A simplified model is used which compares the ammonia load with an estimated nitrification rate at reduced aeration (Eq. 1 and 2). If the load is higher than the nitrification rate, full aeration is triggered after a delay time. The delay is necessary to take the hydraulic retention time in the anoxic zone into account. The combination of feed-forward and feed-back is implemented by a maximum condition.

\[
r_{\text{init}} = \frac{X_{\text{AUT}} \cdot \mu_{\text{max},T} \cdot t_{\text{int}} \cdot \text{Vol}_{\text{BB}}}{Y_{\text{AUT}}}
\]

where:
- \( r_{\text{init}} \) = Nitrification rate (Number of nitrifiers)
- \( X_{\text{AUT}} = 90 \text{gCSB/m}^3 \) (Max. growth rate at 20°C)
- \( \mu_{\text{max},20} = 1 \text{[1/d]} \) (Max. decay rate = \( \mu_{\text{max}} \cdot \exp(0.105 \cdot (T-20°C)) \))
- \( Y_{\text{AUT}} = 0.24 \text{[g CSB/g N]} \) (Autotrophic yield)
- \( t_{\text{int}} = 0.15 \text{[-]} \) (Part of aerated time at intermittent aeration)
- \( \text{Vol}_{\text{BB}} = 2100 \text{m}^3 \) (Reactor volume)

The number of nitrifiers depends on the mean influent load of ammonia:

\[
X_{\text{AUT}} = \frac{L_{\text{NH}_4} \cdot Y_{\text{AUT}} \cdot \text{SRT}}{\text{Vol}_{\text{BB}} \cdot (1 + b_{\text{AUT}} \cdot \text{SRT})}
\]

where:
- \( L_{\text{NH}_4} \) = Mean NH₄-N influent load
- \( \text{SRT} \) = Sludge retention time
- \( b_{\text{AUT}} \) = Mean decay rate = \( b_{\text{AUT},20} \cdot e^{(0.105 \cdot (T-20°C))} \)

Besides the current DO control system operating at 15°C, four main versions were investigated (Table 1). Version 1 includes a feed-back control of the DO set-point based on ammonium sensors at the end of the aeration tanks, whereas V1a comprises additional oxygen feed-back control of the valve serving the last two aeration registers. Version 2 combines the feed-back control of version 1a with a feed-forward control based on an ammonium sensor in the primary effluent. Version 3 comprises a controlled dosage of digester supernatant based on the NH₄ load in the primary effluent and version 3a a separate treatment of the supernatant.
Case Studies

The results show that there is an enormous potential for measuring and control technology to reduce operating costs and simultaneously improve effluent quality. The best control version without separate supernatant treatment (V3) reduces the energy cost by 25% and precipitants addition by more than 50% compared to the current version. If the effluent load tax is also taken into account, a total cost reduction of about 30% in relation to the actual situation can be attained. Looking at the benefits, the savings in energy of about CHF 425,000/a greatly exceed the additional annual costs of about CHF 50,000 for the measuring and control system and its operation. Net savings increase to about 1,400,000 CHF/a if the effluent tax (225,000 CHF/a) and the reduction of precipitants and sludge disposal (800,000 CHF/a) due to the biological P-removal are included (Figure 8).

Figure 8: Modelled ammonia and nitrate load (left) and annual costs (right) for investigated control concepts

The version (V3a) with separate digester supernatant treatment increases net energy savings by another 80,000 CHF/a (difference of aeration energy for the oxidation of 300 t NH4/a supernatant separately instead of by activated sludge treatment). Total net savings then increase to about 2,400,000 CHF/a (effluent tax: 550,000 CHF/a; precipitants and sludge reduction 1,300,000 CHF/a due to biological P-removal) from which about 400,000 CHF/a have to be deducted for separate supernatant treatment (Siegrist et al., 2004). The total nitrogen elimination improves to better than 80% (Figure 9).

Figure 9: Total net savings compared to V0 incl. energy costs, effluent load tax and P-precipitation

The examined feed-forward control did not improve the effluent conditions because all control versions fall below the effluent limit of 2 mg NH4/l. Feed-forward control decreases the peaks in energy consumption caused by ammonia-based feedback. This is an advantage because the energy price takes into account the maximum electrical power uptake.
Case Studies

The dosage of de-icing wastewater will not significantly increase nitrogen elimination after the implementation of powerful NH₄ control. But it could still be added during low COD loads to improve denitrification, for instance at weekends, and to improve enhanced biological P-removal. To model this effect, it must be known whether the de-icing wastewater (mainly glycol) is a suitable substrate for the biological P-uptake. Another alternative is to add the de-icing wastewater to the digesters to generate biogas and energy.

The simulation results still involve some uncertainties because of the artificial database and general model limitations. In particular, the model prediction for denitrification and enhanced biological P-removal during low oxygen concentration is of limited accuracy. Other limitations are the response times of the sensors and the actuators, which were not taken into account in this study. Low oxygen concentrations could also increase the nitrite concentration and the bulking sludge production and thus inhibit the biological P-uptake. The above results and the potentially negative effects of low oxygen concentrations will therefore have to be investigated in practice.

Implementation

A discussion of how to further improve the total nitrogen elimination at WWTP Werdhoelzli will be based on the simulation study (Rieger and Siegrist, 2003b) as well as a second study of the implementation of the AI-concept (Rieger and Siegrist, 2003c). Besides ammonia-based aeration control, the separate treatment of the digester supernatant is taken into account. Full-scale implementation is planned for the end of 2005.
**WWTP Morgental**

The WWTP Morgental (Figure 10) is a single-stage activated sludge plant built in 1975 for the elimination of organic matter of 83,000 p.e. Since 1994, the plant has had to nitrify the wastewater of 42,000 p.e. During the upgrading, two reactors were separated for pre-denitrification. Some 35,000 p.e. are currently connected to the plant (Frommhold, 2001). In 1999 and 2000 additional digester supernatant from a nearby WWTP was treated. The clarified wastewater is discharged into Lake Constance.

WWTP Morgental is not well suited to aeration control. It consists of six lanes, and each lane in the biological stage is divided into two sub-lanes. The aeration system consists of four equal root-type blowers whose output cannot be reduced below a minimum of 70%. This leads to step changes in the aeration capacity during the speed-up or shutdown of the blower unit. Moreover, the blower unit cannot be throttled to the required minimum during the night hours or other periods with low loading. The air distribution is designed as a one-collector system. Since no stabilizing pressure control is possible (due to the step changes), the aeration of the single lanes is quite different and variable. The calculation of the aeration capacity is based on the average DO concentration of all the lanes. The valves of the single lanes are used for DO control in the lanes. The intention was to use the valves only for fine-tuning the air distribution, but in reality the control loops do not have enough control power to reach the set-point, thus resulting in a varying oxygen input in the different lanes. Moreover, the wastewater distribution is not equalized. Lanes one to three are supplied with less particulate matter than lanes four to six. The outermost left- and right-hand lanes are also supplied with more particulate compounds.

**Measuring locations:**
- MP1: Raw wastewater
- MP2: Effluent primary clarifier
- MP3: Influent lane 1
- MP4a/b: Non-aerated reactors lane 1
- MP5a/b: Aerated reactors lane 1
- MP6: Effluent lane 1
- MP7: Effluent secondary clarifier (Q; TSS)
- MP8: Effluent secondary clarifier (sampler)

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Figure 10: WWTP Morgental with measuring locations
Case Studies

The plant is equipped with membrane aerators so that the aeration can be switched off completely. The DO control loop uses a DO probe in the middle of the first aerated reactor. Only one of the two sub-lanes is equipped with a DO sensor.

Goal definition

The main goal at WWTP Morgental was to reduce the energy consumption, since no effluent quality tax and no other limits for total nitrogen exist. Enhanced biological phosphorus removal was also outside the scope of the study.

Data quality

An extensive data quality control was performed at WWTP Morgental (Thomann, 2003; Frommhold, 2001). It included the evaluation of all flow and concentration measurements. The complete operating programme for the various measurements in the laboratory was analysed, inclusive of testing the micropipettes, scales etc. Finally, the fluxes were evaluated by means of combined mass balances (Thomann, 2003). Numerous in- and on-line devices were installed on the plant to monitor its processes and provide an input for the control loops. A new monitoring concept was developed on the basis of this experience (Thomann et al., 2002; Rieger et al., accepted a). In November 2001, six different on- and in-line sensors for ammonia were tested according to ISO 15839 (2003) as well as in field operation (Rieger et al., 2002c). The measured response times of the tested analysers can be found in Rieger et al. (2003a).

Simulation study

It could be shown in the simulation study (Rieger and Siegrist, 2002a) that the WWTP Morgental has great potential for increasing the nitrogen elimination and reducing the energy consumption. It can be made available through the use of suitable measuring and control measures.

On the basis of intensive measuring campaigns of 10 and 11d respectively, the plant model was calibrated and validated by using the ASM3 as biokinetic model (Gujer et al., 1999) with a parameter set for Swiss municipal wastewater (Koch et al., 2000). The simulated control concepts take the technical and process constraints of the plant into account. The following control concepts were investigated:

Table 2: Investigated control concepts in a simulation study for WWTP Morgental

<table>
<thead>
<tr>
<th>No.</th>
<th>Control concept</th>
<th>Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Actual situation</td>
<td>DO set-point = 2 mg/l</td>
</tr>
<tr>
<td>1</td>
<td>DO set-point adjustment due to the ammonia concentration</td>
<td>If NH₄,BB &lt; 1.5 mg/l, than DO set-point = 0.5 mg/l If NH₄,BB &gt; 1.8 mg/l, than DO set-point = 2.0 mg/l</td>
</tr>
<tr>
<td>2</td>
<td>On-off of the blowers due to the ammonia concentration</td>
<td>If NH₄,BB 5 Min. &lt; 1.5 mg/l =&gt; Blower 30 min off If NH₄,BB within time interval &gt; 1.8mg/l =&gt; Blower on</td>
</tr>
<tr>
<td>3</td>
<td>As concept no. 2 plus feed-forward control</td>
<td>Time delay FF control = 25 min Relation NH₄ influent load/nitrification capacity (Eq. 1 and 2) [X_{AUT}=80gCSB/m^3 \text{, Volume} = 458 m^3, t_{int} = \text{Part of aerated time at intermittent aeration} = 0.15 \text{ Relation set-point aeration on} = 1.8 \text{ Relation set-point aeration off} = 1.6 \text{ Combination feed-back and feed-forward by maximum condition}</td>
</tr>
<tr>
<td>4</td>
<td>As concept no. 3, but with increased DO set-point for feed-forward control</td>
<td>DO set-point at feed-forward = 3 mg/l</td>
</tr>
</tbody>
</table>
All the concepts were tested with the actual blower limitation due to the step changes and with an optimized blower unit where a linear change in capacity was possible. The comparison resulted in a difference of 1-2 % reduction in energy consumption if the blower unit was optimized. The absolute cost reduction is between 350 and 1000 CHF/a. For the basic state, a higher reduction of 1800 CHF/a can be attained due to insufficient control power for throttling the aeration capacity to a minimum except with intermittent aeration.

The evaluation shows that the on-off concept combined with feed-forward control on 3 mg DO/l (concept 4) gives the best results with respect to effluent concentrations and energy consumption. The feed-back part guarantees aeration according to the requirements and the feed-forward part gives the signal for increased aeration during peak loadings. Use of a DO set-point of 3 mg/l during peak loadings guarantees that enough oxygen is available in both aerobic reactors (Figure 11 and Figure 13).

Figure 11: DO concentrations in the second aerated reactor for different feed-forward control concepts

Figure 12: Ammonia concentration in the second aerated reactor for different feed-forward control concepts
The reduction potential of the energy consumption reaches 26,000 CHF/a for the selected concept, which is 30% less than the actual energy requirement. If an effluent quality tax is additionally applied, the increased nitrogen elimination yields a reduction potential of 65,000 CHF/a (Figure 14) or an increase in the nitrogen elimination by 48% compared with the actual capacity (Figure 15).
Figure 16: Reduction potential for energy consumption for the modelled control concepts

For a cost-benefit calculation, the annual costs were estimated as 12,000 CHF/a including investment and operational costs for a lifetime of 10 years with an interest rate of 5 %. In relation to the energy reduction, this results in a net benefit of 14,000 CHF/a. If an effluent quality tax is taken into account, the net benefit would increase to 53,000 CHF/a.

**Implementation**

The control concepts were applied in stages due to the technical and financial constraints. After first measuring campaigns and an extensive data analysis and evaluation, the start situation could be characterized as follows:

- The aeration capacity could not be reduced to the required minimum at low loading situations (the blower unit has enormous over-capacities after changing to fine-bubble aeration)
- Dosing of digester supernatant in one pulse resulted in effluent peaks of up to 10 mg/l (or more than 70 mg/l in the influent to the biological stage)
- Unequal distribution of wastewater
- Unequal distribution of air
- DO sensors only in one of two sub-lanes

**First optimization step**

The first step was to equalize the dosing of digester supernatant and to introduce intermittent aeration on the basis of the average DO concentration in order to prevent DO saturation during the night hours.

During the period of intermittent aeration and due to the unequal air and wastewater distribution some lanes do not get enough oxygen and others run into DO saturation. In the aeration phase, the blower control loop tries to reach the DO set-point of 2 mg/l. However, the actual value for the controller is the average DO concentration of all lanes with the assumption of equal DO concentrations in all lanes. Since the DO controller of the single lanes has insufficient control power, this leads to a DO deficiency in some lanes and consequently to increased ammonia concentrations in the effluent from the entire plant.

A first intensive measuring campaign was carried out to obtain data for calibrating the dynamic simulation model. A tracer experiment was used to characterize the hydraulic behaviour of the plant (Abegglen and Haag, 2001).
Case Studies

The ammonia control concepts were also tested in one pilot lane during this phase. The plant model was validated (Hess, 2001) with a second intensive measuring campaign (with a DO set-point adjustment due to the ammonia concentration). Accordingly, it was decided to implement the ammonia control at the whole plant. A simulation study was carried out to predict the reduction potential of the energy consumption and the nitrogen discharge.

In the middle of this phase, the butterfly valves in lanes 1 and 2 were replaced by iris valves in order to test the effect of more suitable valves on the power of the DO controller. The result was good power if the DO concentration was higher than the set-point because the influence of the other lanes predominates at DO concentrations below the set-point.

Second optimization step

To reduce the investment costs, only three ion-sensitive ammonia sensors were installed in the lanes with the higher loads (on the basis of experience). During this phase, all the ammonia feedback control concepts modelled in the simulation study were tested. The DO set-point adjustment was applied using an intermittent aeration concept. Due to financial restrictions, the feed-forward concepts were not applied to the plant. The average of the three ammonia sensors was used as the input to the control loops.

The result was that the average ammonia concentration could be kept near the set-point of 1.5 mg N/l, but the concentrations in the lanes varied strongly. Moreover, the DO concentrations in the lanes varied so greatly that one lane had DO concentrations close to zero during the intermittent aeration (Figure 17). The DO concentration also varied between the two sub-lanes due to the lack of a second DO probe and additional actuators to control both lanes.

![Figure 17: DO concentrations in the different lanes during the second optimization step](image)

The conclusions of this phase were:

- Due to the averaging, the control loop was unable to equalize the varying ammonia concentrations
- The air distribution during the intermittent phase was insufficient
- The air distribution between the two sub-lanes was insufficient

Third optimization step

In this step, the following measures were taken to overcome the problems identified:

- Automatic equalization between the lanes equipped with ammonia sensors through a decrease of the DO set-point in the lanes with a higher nitrification rate
- Increase of the sludge retention time in the lanes without ammonia sensors
- Replacement of the remaining butterfly valves by wedge-gate valves (lanes 3 – 6)

After some fine-tuning of the valve control parameters, the result was acceptable, although the air distribution during intermittent operation is still critical. The ammonia control is currently not in operation due to technical problems with the ion-sensitive ammonia sensors.
Due to these sensor problems, the benefit resulting from the measures could not be evaluated over a longer period within the schedule of this thesis. The last measuring campaign carried out by EAWAG followed the second optimization step. Within this period and when the sensors worked, the reduction of the energy consumption was less than the potential calculated in the simulation study, but in the range of 20%. At the same time, the nitrogen elimination increased by approximately 40%.

**Conclusion**

It could be shown that ammonia control leads to a significant reduction in energy consumption and in an increase of nitrogen elimination even with unfavourable plant designs. The cost-benefit analysis for WWTP Morgental (based on the simulation study) results in a ratio of 0.46 between the annual costs (amortization of investment and operational costs for service, maintenance and chemicals) and the potential energy reduction.

The acceptance at least of the control measures could be described as good. This was mainly due to the installation of on-line devices which supply information about the dynamic behaviour of the plant. The problems (e.g. dosage of digester supernatant) could not be detected without continuously measuring devices, since only 24-h composite samples were analysed.
WWTP Thunersee

WWTP Thunersee is an activated sludge plant mainly treating municipal wastewater of 130,000 p.e. (actual and design capacity) with an industrial influent of approximately 30,000 p.e. After the upgrading of the biological stage in 1998, the plant operates according to the AAO process scheme for enhanced biological phosphorus removal (Figure 18) and consists of two lanes. Each lane is divided into two sub-lanes in the biological stage and is connected to four secondary clarifiers (Figure 19).

An effluent quality limit for total phosphorus of 0.5 mg P/l is fixed by the authorities. In order to meet this limit, a basic chemical precipitation is applied in addition to the Bio-P.

The plant was already able to control the aeration in each reactor in several ways on the basis of DO and ammonia. A blower unit is responsible for the parallel reactors in the two sub-lanes (Figure 20). One blower unit is controlled by a DO control loop based on the average DO concentration of the two sub-lanes. The air distribution is also controlled by the DO concentration. The valve of the sub-lane with the higher DO concentration is throttled. The air supply to the first reactor can be reduced by intermittent aeration. The second reactor can be controlled by means of a DO set-point adjustment in five steps based on the NH₄ concentration.
Goal definition

The goal of the study at WWTP Thunersee was to reduce the operational costs. Because of the effluent quality tax levied by the canton of Bern, the main optimization option is to increase the biological phosphorus removal and the nitrogen elimination. The energy consumption also represents a significant share of the operational costs and its reduction is consequently the second goal of the study.

Data quality

At WWTP Thunersee too, great efforts have been made to check the quality of the measurements. Unlike the case of WWTP Morgental, however, EAWAG only supplied the methods and acted as a contact in the event of questions. This approach started a whole campaign of plant analysis by the plant staff. The acceptance of their own measurements increased greatly after the campaign, although an erroneously calibrated photometer and imprecise test kits had been detected. A photometer was consequently acquired from another manufacturer and used for the subsequent measurements.

The response times of all important on-line devices were detected with special experiments. For on-line analysers with external probe filtration (i.e. a filtration unit outside the reactor with a relatively high required feeding rate of 1-4 m³/h and therefore a heavy submerged feeding pump), a method was developed using highly concentrated standard solution as a tracer. A pressure-resistant pump was used to dose the standard directly behind the submerged feeding pump of the filtration unit. Switching the dosing pump on or off caused a step change in the concentration of the liquid fed to the analyser.

All on-line sensors were monitored using a software tool based on the monitoring concept developed for this purpose (Rieger et al., accepted a).

Simulation study

The simulation study (Rieger et al., 2002b) was carried out on the basis of an intensive measuring campaign of 10d. The plant model based on the ASM3 with the EAWAG Bio-P module (Rieger et al., 2001) was only calibrated for the first data set. During the calibration, the inadequate modelling results in the last anaerobic reactor could be explained by insufficient mixing and back flows between the non-aerated reactors.

The control concepts in Table 3 were investigated:
Table 3: Investigated control concepts in the simulation study for WWTP Thunersee

<table>
<thead>
<tr>
<th>No.</th>
<th>Control concept</th>
<th>Parameter</th>
<th>Control concept</th>
<th>Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Actual situation (IR in fourth reactor)</td>
<td>DO set-point in both reactors = 2 mg/l Internal recycle in 4th reactor</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Basic state for study (IR in fifth reactor)</td>
<td>DO set-point in both reactors = 2 mg/l Internal recycle in 5th reactor</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Reactor aer1+aer2: DO set-point adjustment based on NH4</td>
<td>aer1: NH4,BB &lt; 1.6 mg/l =&gt; DO set-point = 0.5mg/l NH4,BB &gt; 1.8 mg/l =&gt; DO set-point = 2mg/l aer2: NH4,BB &lt; 1.3 mg/l =&gt; DO set-point = 0.5mg/l NH4,BB &gt; 1.5 mg/l =&gt; DO set-point = 2mg/l</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>aer1: On-off control aer2: Basic state</td>
<td>aer1: NH4,BB &lt; 1.6 mg/l =&gt; intermittent aeration: 30 min on/30 min off NH4,BB &gt; 1.8 mg/l =&gt; DO set-point = 2mg/l aer2: DO set-point = 2 mg/l</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>aer1: On-off control aer2: DO set-point adjustment based on NH4</td>
<td>aer1: NH4,BB &lt; 1.6 mg/l =&gt; intermittent aeration: 30 min on/30 min off NH4,BB &gt; 1.8 mg/l =&gt; DO set-point = 2mg/l aer2: NH4,BB &lt; 1.3 mg/l =&gt; DO set-point = 0.5mg/l NH4,BB &gt; 1.5 mg/l =&gt; DO set-point = 2mg/l</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Four-step controller</td>
<td>Concept 5 + feed-forward control based on NH4-NPC (Eq. 1 and 2) Time delay feed-forward control = 15 min Relation NH4 influent load/nitrification capacity Relation set-point aeration on aer1 = 2: DO set-point 2 mg/l Relation set-point aeration off aer1 = 1.8: acc. to 4-step controller Relation set-point aeration on aer2 = 1.4: DO set-point = 2 mg/l Relation set-point aeration off aer2 = 1.2: acc. to 4-step controller</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Four-step controller combined with feed-forward control</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 21: Scheme of the four-step controller

After evaluation of the results, concept 6 (a four-step controller combined with a feed-forward part) was selected as the best choice with respect to effluent-quality tax, energy consumption, dosing of precipitants and sludge disposal. The controller reduces the air supply into the two reactors in steps on the basis of an ammonia measurement at the end of the last aerated tank. The feed-forward controller assures greater safety with respect to peak loading and allows the feedback controller to be run at the optimum without additional risk factors due to the delayed signal.

The annual costs arising from the need for additional measuring devices and control approaches were estimated for the cost-benefit calculation. They consist of investment and operational costs for a lifetime of 10a with an interest rate of 5%. The reduction potential for effluent-quality tax, precipitants and precipitation sludge disposal is 40%, or 260,000 CHF/a in absolute numbers (Figure 22). The energy reduction potential was calculated as 30% or 120,000 CHF/a. The reduction in energy consumption alone would be much higher than the annual costs of 16,000 CHF/a. The resulting net revenue is 380,000 CHF/a.
As regards the environmental benefit, the nitrogen elimination could be increased by 135 t N/a or 60% compared to a full aeration in both reactors (Figure 23). This is 5% of the 2600 t N/a agreed by Switzerland in order to reduce nitrogen discharge into the river Rhine (see chapter General Introduction).

The reduction potential for phosphorus is also high due to the better denitrification (Figure 24). No precipitation was taken into account in the simulation study, but in the analysis all phosphorus above 0.5 mg/l was calculated as precipitated. An increase in the phosphorus eliminated by Bio-P leads to a lower consumption of precipitants and thus to less precipitation sludge to be disposed of. When the four-step controller was used, the biological phosphorus elimination increased by 50% or 12 t P/a. One part of this reduction is caused by enhancement of the anaerobic zone achieved by guiding the internal recycle into the 5th instead of the 4th reactor.
Case Studies

Implementation

The findings of the simulation study provided the basis for discussing implementation of the results at the plant with the plant manager and the operator-in-chief. It was decided to test three different control concepts against a basic state (Table 4 and Figure 25). The basic state includes an increase of the anaerobic zone to four instead of three reactors. Moreover, the partition walls between the non-aerated reactors were modified in order to achieve better mixing and prevent back flows. In the test phase, the first of the two lanes was used for the experiments while the second lane was operated with full aeration and served as a reference.

Table 4: Implemented control concept and duration of the experiments in WWTP Thunersee (schemes in Figure 25)

<table>
<thead>
<tr>
<th>No.</th>
<th>Control concept</th>
<th>Duration of experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>aer1: Intermittent aeration&lt;br&gt;aer2: DO set-point = 2 mg/l</td>
<td>Nov. 2002 – Feb. 2003</td>
</tr>
<tr>
<td>2</td>
<td>aer1: Intermittent aeration (2 states)&lt;br&gt;aer2: DO set-point = 2 mg/l</td>
<td>Feb. 2003 – March 2003</td>
</tr>
<tr>
<td>0</td>
<td>Basic state (DO set-point 2 mg/l in both reactors)</td>
<td>March 2003 – April 2003 and July 2003</td>
</tr>
<tr>
<td>3</td>
<td>aer1: Aeration based on blower capacity of aer2&lt;br&gt;aer2: DO set-point adjustment based on NH4,BB</td>
<td>June 2003</td>
</tr>
</tbody>
</table>

The comparison of the experimental and reference lanes shows a reduction in energy consumption of 10% for control concept no. 1, 11% for no. 2 and 16.5% for no. 3 (Figure 26) compared with the basic state (DO set-point of 2 mg DO/l in both reactors).
Figure 26: Measured reduction in energy consumption

The reason for the limited reduction is the insufficient control power of the implemented control concepts (Figure 27). The mean value of ammonia in the last aerated reactor during the test of the third control concept was 1 mg N/l, whereas a concentration of 2 mg N/l should be maintained by the ammonia controller. Nevertheless, the total nitrogen elimination was increased by 40% with the third control concept (Figure 28). The results were calculated by comparing the 24-h composite samples of the experimental and reference lanes. A reduction potential for phosphorus precipitation cannot be given because a basic precipitation took place in both lanes. The precipitant dosage is controlled manually by the operators on the basis of the on-line measurements for phosphate and the 24-h composite samples.

Figure 27: Ammonia concentration during the test of the third control concept

Figure 28: Measured reduction in nitrogen elimination
Case Studies

Conclusion

The reduction in energy consumption and total nitrogen discharge achieved is less than the results obtained in the simulation study for the best scenario, but still represents a significant improvement with 16% (energy) and 40% (total nitrogen). The better results obtained in the simulation are due to a higher reduction potential of the air supply and consequently a better control power for reaching the ammonia set-point.

The cost-benefit analysis for WWTP Thunersee results in a ratio of 0.1 between the annual costs (amortization of investment and operational costs for service and maintenance) and the reduction in energy consumption and effluent-quality tax for nitrogen.
PRACTICAL ASPECTS OF AERATION REDUCTION IN WWTPs

The control of aeration in an activated sludge system by ammonia can lead to a significant reduction of the total energy consumption in conjunction with decreased effluent concentrations of total nitrogen. However, this is only one part of the cost calculation. The need for reliable and accurate sensor values as an input for the control concepts requires more monitoring and service operations to be performed. Moreover, there are still some reservations that low oxygen concentrations can lead to serious problems in plant operation. During several measuring campaigns, the practical and cost aspects of a significant reduction of aeration were evaluated.

Goal definition

Two hypotheses for the effects of low oxygen concentrations were formulated and examined:

- Low oxygen concentrations lead to increased growth of filamentous bacteria resulting in the production of foam and scum.
- Low oxygen concentrations lead to higher concentrations of nitrite in the effluent.

In addition, a long-term evaluation should evaluate practical problems occurring as a result of greatly reduced oxygen concentrations.

Methods

The first hypothesis was evaluated using fluorescence in-situ hybridization (FISH) to measure the abundance of M. parvicella and nocardioform actinomycetes. A rapid quantification method was applied which was suitable for practical use in wastewater treatment systems (Hug et al., 2003). In addition, the foam coverage of the reactors was monitored and the foaming potential evaluated using a batch test method developed by Ho and Jenkins (1991).

The accumulation of nitrite was monitored with a new submerged spectrometer sensor (Rieger et al., accepted b).

First Results and Discussion

Hypothesis 1: Microthrix parvicella always occurred at very high concentrations although it decreased during one time period. This trend was identical in both lanes and is consistent with the commonly observed seasonal variations of this microorganism. Hence, the reduction does not seem to be caused by the changed conditions due to the implemented control strategies. As regards nocardioform actinomycetes, none of the typical branched filaments were found but rather non-filamentous types that did not vary over time. The variations of the foam coverage and foaming potential could be linked to the type and amount of the P-precipitants (FeClSO₄, AlCl₃) but not to the implemented control strategies.

Hypothesis 2: The nitrite measurements (Figure 29) showed increased concentrations if the aeration is reduced only in the first aerated reactor. When a reduction was implemented in both reactors, the concentrations increased at first, but decreased to normal values of less than 0.1 mg/l after one week. The differences between laboratory and sensor values can be related to ongoing reactions in the 24h-composite sample. Although the concentrations in the reference lane also increased, the nitrite concentrations in the pilot lane were higher.
Long-term evaluations: Experience showed that the maintenance and monitoring outlay using advanced aeration control plays a major part in the cost calculations. Depending on the measuring device, this outlay is between 1 and 3 h/week and device on average. This means that at most plants the staffing requirements will cause by far the main fraction of the annual costs.

At WWTP Thunersee, a significant part of the cost reduction due to lower average aeration was lost again due to short peaks of high energy consumption, since the energy price for this plant takes into account the maximum electrical power consumption in a quarter of an hour.

After three years of applying the control strategies at WWTP Morgental, serious corrosion problems of the concrete were detected at the end of the second aerated reactor. They were caused by permanently settled and therefore aerobic sludge. The inadequate mixing in the intermittently aerated reactor was due to excessive manual reduction of the aeration in the last sector of this reactor.

**PROJECTION OF REDUCTION POTENTIAL TO SWITZERLAND AS A WHOLE**

In order to project the reduction potential of the ammonia control concepts to Switzerland as a whole, the percentage of wastewater which is treated in nitrifying WWTPs has to be defined. Since the latest official information dates from 1995, an estimation of the current situation is needed. Because of the incorporation of nutrient removal in many of the larger Swiss WWTPs, it is assumed that the percentage increased up to 40% or 5.25 million p.e. Assuming a reduction potential in energy consumption of 20%, this will reduce the annual consumption by 20 million kWh/a. With an energy price of 0.15 CHF/kWh, this amounts to a reduction potential of 3 million CHF/a.

**CONCLUSIONS**

The results show that a great benefit can be achieved in terms of energy consumption and nutrient removal, but implementation of advanced aeration control is still a complex task. It should take into account not only the measuring and control system but also practical aspects such as the outlay required to monitor and maintain the sensors. A well-adapted control strategy must place special emphasis on the technical equipment and the effect of peak consumption on the energy price and not only on the possible cost reduction due to lower average aeration. Possible cost drawbacks due to filamentous growth and foam formation should be considered, although no direct influence of the control strategies on the abundance of M. parvicella or nocardioform actinomycetes was observed.
The application of measuring and control systems requires greater knowledge and effort on the part of the operators. In the first place, the on-line sensors have to be maintained and monitored. The lack of a systematic monitoring concept will jeopardize optimum operation.

The measuring and control equipment should be regarded as a single system. In practice, problems often arise because the time delays resulting from the sensors, aeration system or oxygen input are not taken into account during the planning phase. Dynamic simulation is a suitable tool for explicitly including these delays. Another problem is the control power needed to reach the given set-points. In the study for WWTP Thunersee, it could be shown that the reduction potential in the air supply is insufficient to keep the ammonia concentration near the set-point.

The crucial point for practical applications of the control concepts is their economic viability. Most plants in Switzerland can break even only by means of energy and precipitant reduction. An effluent-quality tax exists in only two cantons. As regards the sustainable application of measuring and control concepts, it should be decided in detail if the benefit exceeds the real costs. The best solution will be the simplest concept which still yields a significant benefit in comparison with the annual costs.

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Case Studies


CONCLUSIONS
Conclusions

GENERAL

It could be shown that aeration-control concepts based on ammonia lead to a significant reduction of energy consumption, total nitrogen discharge and – if free capacities exist – to increased biological phosphorus removal (Bio-P). The results were obtained on the basis of detailed simulation studies and full-scale applications. The full-scale results validated the reduction potential of the simulation studies. Besides the technical questions, operational and socio-economic aspects were also taken into account.

MEASURING EQUIPMENT

Depending on the goal of the measurement, different demands are made on the measuring devices. A short response time is often of major interest for control applications, whereas the accuracy is most important for effluent monitoring. Response times of up to 35 minutes have been measured, and even higher values are achieved with the standard filtration systems widely used today. A short response time becomes significant in cases where the time constants of the controlled process are similar to or smaller than the sensor response time. For control purposes, a response time of 10 to 20 minutes should be aimed at, but highly dynamic systems (e.g. DO control) may need an even shorter delay. These demands strongly favour in-line systems without sample preparation.

In this work, ion-sensitive in-line sensors were applied at various locations and evaluated for control purposes. The advantage of the measuring principle is its minimal response time and applicability at locations where conventional analysers with a filtration unit reach their limits (e.g. influent measurements for feed-forward control). Among its disadvantages are drift effects, which make weekly calibration necessary, as well as strong cross-sensitivities to disturbance ions (mainly potassium in the case of ammonium). Taking the pros and cons into account, the general applicability of the sensors to aeration control was demonstrated. Thanks to its all-purpose applicability as well as its low investment and operational costs, the new in-line sensor subsequently opens up new possibilities for the application of more sophisticated control strategies such as feed-forward control.

DATA QUALITY

On-line measurements form the basis of the control system. To obtain reliable and properly operating systems, a certain input accuracy has to be assured. The first step is to prevent systematic measuring errors, and the second step is to calculate the uncertainties of the instrument. A knowledge of the uncertainties allows the controller to be parameterized with the required safety.

During this work, a monitoring concept was developed which uses comparative measurements and allows measuring errors and poor calibration to be identified. The concept was implemented in a software environment and tested on various plants in Switzerland. A procedure for calculating the uncertainties of a measuring device based on comparative measurements is also proposed. It is suitable for on-line probes during field application and takes the whole measuring chain into account.
Conclusions

AERATION CONTROL

Most of the control strategies applied in wastewater treatment plants today represent a relatively low level of sophistication. As a rule, the control goal is to keep the oxygen concentration at a fixed level and not regulate the air supply according to the demands of the purification processes. These DO control strategies have proved to yield satisfactory results due to the ample process volume available, which attenuates the incoming peak loads. This makes the process very robust against disturbances and consequently does not need immediate control action.

Nevertheless, more sophisticated control strategies are gaining importance in response to constantly growing demands on effluent quality and optimized plant operation. Ammonia-based control enables the aeration to be tailored to the requirements. Within this work, different control strategies are tested by simulation and in full-scale operation. The best strategy to select depends on the kind of diffusers used (ceramic or membranes), the specific constraints of the plant and the optimization goal. If the main goal is to reduce energy consumption, a DO set-point adjustment based on the ammonia concentration often makes sense, whereas intermittent aeration has the advantage of increasing the total nitrogen elimination due to the often higher control power.

DYNAMIC SIMULATION

Dynamic simulation is a proven tool for predicting the behaviour of a WWTP with the required accuracy. To obtain realistic results for the control actions as well, the time constants of the system have to be taken explicitly into account. In order to transfer the control structure and parameter settings obtained by a simulation study and to achieve similar results in practice it becomes necessary to use realistic models at least for the sensors and the aeration system.

As part of this thesis, a biokinetic model was developed which can predict oxygen consumption, sludge production, nitrification, denitrification and Bio-P. It is based on Activated Sludge Model No. 3 (ASM3) with an additional module for enhanced biological phosphorus removal (Bio-P). The modelling of Bio-P processes is of great interest for plant optimization since reduction of P-precipitants and thus of the precipitant sludge disposal is a major cost factor for WWTPs.

If the response times of the sensors are not taken into account, a simulation study designed to develop or optimize the control concepts of a WWTP has very limited application. Sensor models were consequently developed which can be used for the design and optimization of control systems. As regards the effects of sensor dynamics on control performance, it can be concluded from simulation results that although sensors with high response times can still be suitably adapted to low load situations, they cannot deal sufficiently well with high load peaks. If the sensor dynamics can be considered within the controller design (e.g. for feed-forward control), the effect of sensor delays can be compensated.

The investigation of different aeration control systems in two full-scale WWTPs and a pilot plant showed that the time delay of the aeration system without a controller and oxygen gas exchange amounts to between 4 and 10 min. A model was developed which can be calibrated using step-change experiments. A problem may arise here because often no air-flow sensors are installed in an individual lane, although these are necessary for direct calibration. Indirect calibration of the response time on the basis of the DO concentration is critical due to an inability to identify the parameters for the oxygen transfer and time delay of the aeration system. The oxygen transfer must therefore be calibrated in advance.

As a result, it could be concluded from the case studies that control loops for the regulation of the blower unit based on air-pressure control in the collector often react faster to disturbances than a controller based on the average DO concentration of all the lanes.
SOCIO-ECONOMIC ASPECTS

Socio-economic aspects were identified as an important reason why measuring and control systems do not work in a satisfactory manner over a prolonged period. The reservations held against new control concepts could be linked to differing interests and a lack of sufficient incentives. An existing chain of incentives from the federal agency for the environment down to the plant operator is discussed and recommendations suggested. Major incentives for optimized aeration control are created by an effluent load tax, but this is applied in only two cantons in Switzerland. At plant level it is most important to integrate the operators from the beginning and to give them enough incentives to perform the extra work required by newly installed measuring and control systems. During the design phase, the knowledge of the experts involved must be made available and integrated in the control strategy. Dynamic simulation represents an optimal tool for knowledge integration with respect to control.

CASE STUDIES

The results were obtained from detailed simulation studies on three WWTPs (35,000 p.e., 130,000 p.e. and 600,000 p.e.) and full-scale applications on two of them. The simulation results show that aeration-control concepts based on ammonia can lead to a significant reduction of energy consumption (25-30%) and total nitrogen discharge (30-55%). The reduced aeration increases the phosphorus removal efficiency at Bio-P plants. It can also form the basis for introducing anaerobic phases in nitrifying plants, thus allowing Bio-P organisms to grow-in. This increases the cost-reduction potential thanks to lower precipitant consumption and subsequently a lower level of precipitant sludge disposal.

In principle, the full-scale results validated the reduction potential of the simulation studies. However, the technical, operational and political constraints of the plants prevented the application of the best-rated control concepts from the simulation studies. Nevertheless, the reduction in energy consumption was 20% and 16% for WWTP Morgental and WWTP Thunersee respectively. The nitrogen discharge could simultaneously be decreased by 40% at both plants.

The planning of advanced aeration control should include not only the measuring and control system but also operational aspects such as the effort required to monitor and maintain the sensors or the technical equipment of the plant. Possible cost drawbacks due to filamentous growth and foam formation should be considered, although no direct influence of the control strategies was observed. The enrichment of nitrite due to low oxygen concentrations was also investigated but no sustained influence was measured here either.

The proposed aeration control concepts are often restricted by the limited control power available to reach the given set-points. In the study for WWTP Thunersee it was shown that the reduction potential in air supply is insufficient to keep the ammonia concentration near the set-point. Taking advanced aeration control into account as early as the planning phase can help to overcome these limitations.

The crucial point for the practical application of the control concepts is their economic viability. Most plants in Switzerland can achieve breakeven only by means of energy and precipitant reduction. It should be decided in detail if the benefit exceeds the real costs of a sustainable application of measuring and control concepts.
OUTLOOK
Outlook

The difficulties occurring in the planning and implementation of measuring and control systems for aeration control are very complex. Improvements can be achieved in the following sectors:

- **Design and implementation**
  - Controllers which are better adapted but still simple enough (e.g. feed-forward control or controllers which take the time delays into account)
  - Dynamic simulation is a suitable tool, but guidelines for simulation studies must be developed to prevent its misuse
  - The proposed models must be validated for controller design and optimization

- **Technical equipment**
  - More appropriate sensors (user-friendly, reliable, short response time, etc.)
  - More appropriate actuators (fast reaction, linear behaviour, sufficient adjusting range, etc. to increase control power)
  - SCADA systems which interpret the data and supply the required information to the operators (mainly graphical interpretation and process-related instead of location-related information)

- **Operation**
  - Minimization of effort to monitor and maintain sensors and actuators
  - Tools for data evaluation at plant level
  - Inclusion of socio-economic aspects (incentives, responsibilities and decision-making authority)
  - Real cost-benefit calculations

Besides the socio-economic aspects, major improvements can be achieved with better measuring equipment and particularly with new systems for data evaluation at plant level. Thus, future efforts should concentrate on the development of a measuring system which combines different monitoring concepts and data evaluation methods. The proposed off-line data quality monitoring concept detects measuring errors and poor calibration. As regards control, however, a compromise must always be made between effort and safety with respect to errors, since not each single value as input to the controller is checked. On-line concepts can be used for control applications, but not all errors can be detected with such approaches. A future general data quality monitoring system could include the following steps:

- **Automatic check of each single value**: This should guarantee the usability and reliability of the signal for control purposes. Many methods have been published in the last few years (Rosen et al., 2003; Stigter, 1997; Ciavatta et al., 2004; Yoo et al., 2004).

- **Regular off-line analysis of comparative measurements**: An off-line concept is presented in this work and should detect systematic errors and poor calibration. It is needed in addition to the on-line analysis because the automatic check can only detect disturbances from a basic state but no constant offset, for instance.

- **A combination of on-line and off-line methods**: If a potential error is detected by the on-line or off-line method, an additional measurement should be triggered to validate the ‘out-of-control’ hypothesis.

- **General data quality monitoring system**: The last step is to integrate other measurements into the evaluation by using all available data including flow measurements and routine lab data. Existing redundancies and process knowledge will then be used to identify errors by calculating mass balances with overlapping boundaries (Thomann, 2003). This approach will allow the mass fluxes, and not only the concentration measurements of a single sensor, to be controlled.
REFERENCES


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