Some control strategies for the activated sludge process

Bengt Carlsson and Carl-Fredrik Lindberg
Systems and Control Group
Uppsala University

Oct 96, Rev Oct 97, Aug 98

Abstract

This material is made for the course "Wastewater treatment" in the Aquatic and Environmental Engineering program. An overview of some control strategies for the activated sludge is given. Problems related to control the dissolved oxygen concentration is treated in some more detail. The sections which are marked with a $*$ are not central in the course.

Contents

1 Background **2**

2 The activated sludge process **2**
2.1 Basic description 2
2.2 Biological nitrogen removal 3

3 Control of wastewater treatment plants **5**

4 Control of the DO in an activated sludge process **8**
4.1 The definition of the oxygen transfer function 9
4.2 The dissolved oxygen dynamics 9
4.3 The control problem 11
4.4 The nonlinear DO controller 11
4.5 Pole-placement with a PI-controller* 13
4.6 Illustration of the control strategy 14
4.7 Cascade control using air flow rate measurements 15
4.8 Control of the dissolved oxygen set-point 15
4.8.1 A practical experiment 17
4.9 Pressure control 19

5 Control of external carbon flow rate **20**
5.1 Motivations 20
5.2 A basic strategy 20

1 Background

The introduction of water closets in the end of the 1800's gradually solved many of the sanitary problems and epidemics related to the traditionally handling of eg. latrines, see Figure 1.

Figure 1: Latrine carrying in Stockholm, drawing from 1828 (från *Avloppsteknik*, Kommunförbundet, 1988

After some time, however, it become more and more obvious that wastewater has to be well treated before it enters a recipient.

Biological treatment of wastewater has a history of around 100 years. In Sweden, biological treatment was introduced after problems with oxygen depletion in the recipients. This was around 1950. Combined biological-chemical treatment was introduced in the 1970's, since eutrophication of lakes due to phosphorus and nitrogen from wastewater was discovered. In 1988, a new Swedish policy was announced, which was based on an international agreement to realize a 50% decrease of the nutrient discharges to the North Sea. The policy proposed more stringent effluent requirements for nitrogen at many Swedish wastewater treatment plants. Also, increased phosphorus removal was proposed for many larger plants. This new demands for nitrogen reduction in wastewater treatment call for more efficient control and operation of the wastewater plants. The purpose of this document is therefore to give an introductory discussion of the use of automatic control in wastewater treatment plants. In particular, the control of the activated sludge process is treated.

2 The activated sludge process

2.1 Basic description

In its simplest form the activated sludge process is a biological process where microorganisms oxidize and mineralize organic matter. A variety of microorganisms are present in the influent wastewater. Some species will adapt to the wastewater treatment processes and proliferate.

Figure 2 illustrates the basic biological renewal process in a wastewater plant. The organic matter enters the plant in several different forms and is converted to other forms by biological processes. The *hydrolysis process* converts larger molecules in the slowly biodegradable matter into smaller, more easily accessible molecules, i.e. into readily biodegradable matter. The speed of hydrolysis may be a constraint in the activated sludge process the influent wastewater mainly consists of slowly biodegradable matter. The reason is that the hydrolysis process is relatively slower than the growth rate of the microorganisms (biomass). The growth rate of microorganisms depends on many things, including amount of biomass (number of microorganisms), substrate (food, readily biodegradable matter), temperature, pH, toxics, etc.

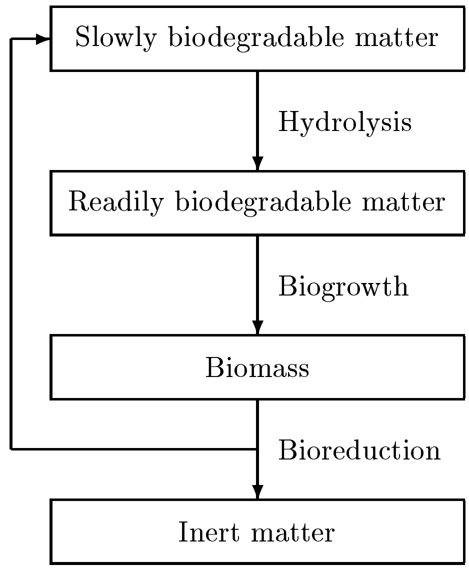

Figure 2: The biological renewal process.

In the activated sludge process, the microorganisms are kept suspended either by blowing air in the tank or by the use of agitators. Oxygen is used by the microorganisms to oxidize organic matter. To maintain the microbiological population, the sludge from the settler is recirculated to the aerated tank, see Figure 3. In order to keep the sludge concentration constant despite of the growth of the microorganisms , sludge is withdrawn from the process as *excess sludge* (also called waste sludge).

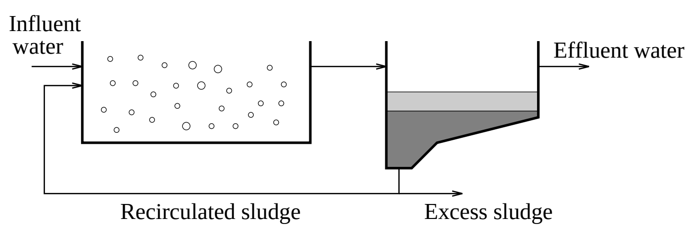

Figure 3: An activated sludge process with an aeration tank and a settler (sedimentation tank, clarifier

2.2 Biological nitrogen removal

Nitrogen is be present in several forms , e.g. as ammonia (NH_3), ammonium (NH_4^+), nitrate (NO_3^-), nitrite (NO_2^-) and as organic compounds. In untreated wastewater, nitrogen is mostly present in the form of NH_4^+ and organic nitrogen.

Nitrogen is an essential nutrient for biological growth. It is one of the main constituents in all living organisms. However, when nitrogen is present in effluent wastewater, problems may arise:

- Ammonia is toxic to aquatic organisms, especially for higher life forms such as fishes.

- When ammonium is oxidized to nitrate, a significant oxygen demand in the receiving water may give rise to a severe depletion of the dissolved oxygen concentration.
- Nitrite in drinking water is toxic, especially for infants.
- Nitrogen is an essential plant nutrient. Overloading can stimulate undesirable growth of aquatic plants and algae. When the plants die, oxygen is consumed by organisms degrading the litter.
- The presence of ammonia in drinking water supplies requires an increased chlorine dosage.

The ammonium can be removed in a two-step procedure. In the first step, ammonium is oxidized to nitrate during aerobic conditions (i.e. dissolved oxygen is present). This process is called *nitrification* and can be described by the following chemical reaction formulas:

$$NH_4^+ + 1.5O_2 \rightarrow NO_2^- + H_2O + 2H^+ \tag{1}$$
$$NO_2^- + 0.5O_2 \rightarrow NO_3^- \tag{2}$$

As seen in the formulas, ammonium is first oxidized to nitrite and then to nitrate.

The nitrate can be converted to nitrogen gas by *denitrification*. This process occurs in *anoxic* environments (oxygen only present as nitrate). The bacterias responsible for denitrification respire with nitrate instead of oxygen. The following simplified reaction formula shows the basic process:

$$2NO_3^- + 2H^+ \rightarrow N_2 + H_2O + 2.5O_2 \tag{3}$$

Anoxic zones in the activated sludge process are necessary to accomplish denitrification. These zones can be placed either in the beginning of the tank (pre-denitrification), see Figure 4, or in the end of the tank (post-denitrification). In a pre-denitrifying system, an extra recirculation flow is usually introduced in order to transport the nitrified water back to the first zone.

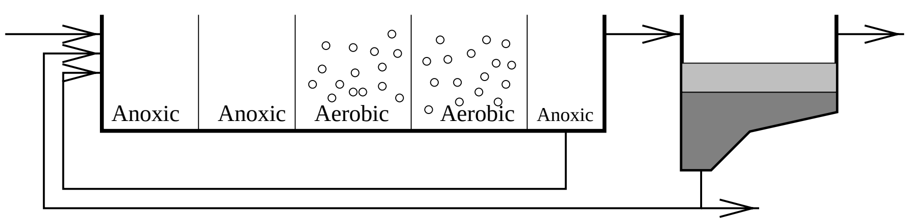

Figure 4: An activated sludge process with pre-denitrification.

The reduction of the nitrate is coupled to the oxidation of an energy yielding compound, normally an organic one. The carbon content in the influent wastewater can be more efficiently used for denitrification process if the anoxic zones are placed at the beginning of the biological reactor. In a pre-denitrifying process the nitrate rich water from the aerobic zones should be recirculated back to the the anoxic zone, see Figure 4. Typically, the recirculated flow rate is three to five times of the influent flow rate. Oxygen present in the anoxic zone makes denitrification less efficient, and more carbon may be required. To reduce the oxygen concentration introduced by the recirculated water, an additional anoxic zone in the end of the activated sludge process can be introduced.

If the denitrification becomes carbon constrained, an external carbon source can be added to better make use of the whole nitrogen removal capacity. Often, the influent lacks sufficient energy to support denitrification, in particular when the anoxic zones are placed after the aerobic zones. A carbon source is therefore normally added in post-denitrification systems.

The activated sludge process can also be extended for biological phosphorus removal but that topic is not covered here.

3 Control of wastewater treatment plants

The allowed levels of pollutants in treated wastewater have become increasingly stringent with time. Taking into account current environmental problems, it is not unrealistic to believe that the this trend will continue. At the same time loads on existing plants plants are expected to increase due to growth of urban areas. This situation demands more efficient treatment procedures for wastewater.

One way to improve efficiency could be to construct new and larger basins, but this is expensive and often impossible since the land required is just not available. Another way would be the introduction of more advanced control and operating systems. This is expected to reduce the need for larger volumes, improve the effluent water quality, decrease the use of chemicals, and save energy and operational costs. Sustainable solutions to the problems of wastewater treatment will require the development of adequate information systems for control and supervision of the process.
Today many plants, special old or small ones, use fairly simple control strategies and many control loops are manually controlled. Control techniques commonly in use include simple PLC-techniques, time control, flow proportional control and PID-control. The following reasons may explain why advanced control have not been extensively used.

- The effluent standards have not been tight enough. Economic penalties for exceeding the regulations along with stricter effluent regulations which are not based solely on long average values could encourage implementation of better control.
- Wastewater treatment is often considered as a non-productive process. Since control systems are expensive it may be difficult to convince a plant manager to introduce a more advanced system, especially when profit can not be guaranteed.
- On-line sensors have been unreliable and require a lot of maintenance.
- Many pumps, valves, and other actuators are not controllable; often they can only be switched on or off.
- The process is very complex and it is not obvious how to control and optimize the plant.
- Few control engineers have devoted their attention to wastewater treatment plants. Further, personnel and managers may have limited knowledge on what automatic control can do to run the plant efficiently.

There is, however, a growing interest in applying efficient control strategies. The reasons for this are most economical:

- Cost effective solutions are becoming more and more important. As the loads on existing plants increase, control and optimization may be able to handle the increasing loads with the same volumes.
- Stiffer requirements on treated wastewater.
- Fees and taxes related to the effluent water quality are making it more expensive to release pollutions.
- The general public's awareness of environmental issues is increasing and more and more focused on issues of sustainability and energy consumption.
- Improved on-line sensors and actuators are being continuously developed.
- More complex process alternatives, which are difficult to control manually.
- Models of the processes in a wastewater plant have been developed over the years which is suitable for model based control.

Application of modern control theory in combination with new on-line sensors and appropriate parts of advanced models has great potential to improve the effluent water quality, decrease the use of chemicals and to save energy and money. New on-line sensors, suitable for use in wastewater treatment are continuously being developed, such as measuring devices for:

- Ammonium.
- Nitrate.
- Phosphate.
- Sludge blanket level (in
- Redox potential.
- MLSS (mixed liquors suspended solids).
- Oxygen uptake rate (respiration rate).
- TOC (total organic carbon)

See also Figure 5 where a prediction of sensor use in wastewater treatments plants in Denmark is made.

New advanced control strategies may involve the use of simplified biological/physical models or black box models. Feedforward control from measurable disturbances can increase the performance of the control. A challenging topic is to consider control of several units or total plant optimization.

Automatic control techniques have been applied to control the dissolved oxygen concentration (DO) in wastewater treatment plants for many years. The reasons include:

- On-line sensors have existed for DO measurements for several years.
- There is much to gain by controlling the DO, since it is very expensive to blow air in the (several meters) deep basins.
- The effluent water quality and process efficiency depend largely on a suitable DO.

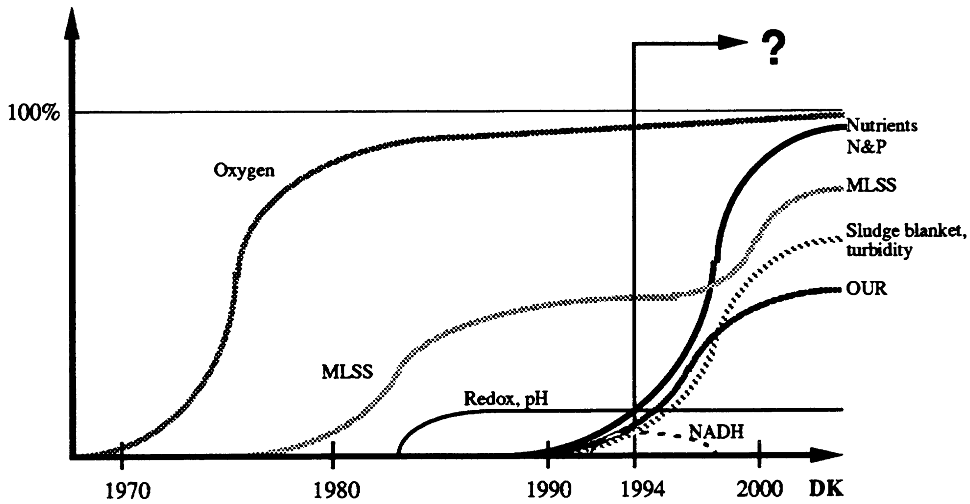

Figure 5: Use of sensors in full-scale control in Denmark.

Further energy saving can be achieved by minimizing the pressure drop in the air valves. A common strategy is to control the air pressure so that the most opened throttle valve is almost completely opened.

On-line ammonium sensors can be used for controlling the set-point of the DO and/or the number of aerated zones. Instead of using a fixed set-point of the DO, the set-point may be determined from the ammonium concentration.

On-line nitrate sensors can be used for external carbon dosage control. The external carbon flow rate may be controlled so that the nitrate concentration is kept low. By use of feedforward control from e.g. influent total organic carbon (TOC) and recirculated nitrate or influent ammonium, disturbances in influent water can more efficiently rejected.

Also, it is important to control the chemical dosage in a wastewater plant, for example when phosphorus is removed by chemical precipitation. A combination of feedback and feedforward control from on-line sensor, flow rates and an experience data base may be useful to obtain an appropriate chemical dosage.

Optimizing the different flow rates in the plant is important. Some of the flows determine the amount of biomass in the system. Maintaining a high concentration of biomass seems to be a tempting approach to improve the plant performance, since a large biomass can remove large amounts of organic material. Unfortunately, the sedimentation capacity may then exceed, and other forms of microorganisms adapt to the high concentrations of biomass, which in turn makes the activated sludge process less efficient.

Large variations in the wastewater flow may be significantly reduced by using buffering tanks or using the sewer tunnels as reservoirs. The variations in influent flow is mostly caused by rain water which leaks into the pipes, or by drainage water. These variations force the plants to work with higher flows during short periods; this is less efficient as compared to a constant flow. In Malmö experiments by using weather radar to optimize the pumping of influent wastewater have been reported. In Göteborg the sewer tunnels are used as reservoirs.

The settler has the dual task of clarifying and thickening the sludge. Its function is crucial to the operation of the activated sludge process. Hence, modeling, diagnostics, and control of the sedimentation process is also an important topic.

The above list of control strategies for wastewater treatment is by no means complete. A key goal in wastewater treatment is to maintain the effluent quality standards at a minimum cost. Obviously it is then not enough to have an efficient control of various subprocesses. One must also consider the total optimization of the plant.

For a control engineer the activated sludge process in a wastewater treatment plant is a challenging topic for several reasons.

- The process is time-varying. It is a biological process where temperature, composition of influent water, amount of biomass, flows, etc, vary in time. It may be nontrivial to design a controller which works during all operating conditions. Further, the process is nonlinear. Examples include the Monod functions ($\frac{\mu S_S}{K_S+S_S}$), and multiplication of states (bilinearity).

- The process has stiff dynamics. It has time constants which range from seconds to months. The problem may often be solved by cascade control. Cascade control means that a fast controller controls a fast sub-process and a slower one controls the set-point of the fast controller.

- The process is multivariable. The process has several inputs and outputs. What should be considered as inputs and outputs are not obvious. An input could, for example, be a set-point for a fast controller, and an output does not necessarily have to be a concentration in the effluent, it could be a concentration in a zone. There are also large cross-couplings, e.g. if a flow is changed, many other variables are affected.

- Many sensors are still not reliable. Much progress has been made in sensor development in recent years. Common problems are that the sensors are fairly noisy, have long response times, require frequent maintenance, and that they drift.

- Large disturbances affect the process. Especially influent flow and influent concentrations are subject to large variation.

In the following restrict the discussion of various aspects of DO control and and a basic strategy for controlling the flow arte of an external carbon source.

4 Control of the DO in an activated sludge process

The dissolved oxygen concentration (DO) in the aerobic part of an activated sludge process should be sufficiently high to supply enough oxygen to the microorganisms in the sludge. On the other hand, an excessively high DO (which requires a high air flow rate) leads to a high energy consumption and may also deteriorate the sludge quality. A high DO concentration in the internally recirculated water also makes the denitrification less efficient. Hence, both for economical and process reasons, it is of interest to control the DO.

One problem in controlling the DO is that the process dynamics is nonlinear. This means that high control performance for all operating conditions may be hard to achieve with a linear controller. In order to overcome this problem, a design method which gives a high performance controller for all operating conditions will be described. The key idea is to explicitly take the nonlinear characteristics of the oxygen transfer function K_La into account in the control design. The design method consists of two separate parts: an estimation part where the K_La is determined and a controller design part. For simplicity, we only describe the controller design part here and assume that K_La is known.

4.1 The definition of the oxygen transfer function

In the dissolved oxygen concentration dynamics, the oxygen transfer function K_La is included. It describes the rate at which oxygen is transferred to the wastewater by the aeration system as a function of the air flow rate.

The most common way to describe the oxygen transfer is by the following equation

$$K_La(u(t))(y_{sat} - y(t)), \qquad y_{sat} > y(t) \tag{4}$$

In (4), the oxygen transfer function K_La only depends on the air flow rate $u(t)$. However, K_La depends also on several other factors, for example type of diffusers, wastewater composition, temperature, design of aeration tank, tank depth, placement of diffusers, etc. The main *time-varying* dependence is on the air flow rate.

The a in oxygen transfer function K_La is derived from the *area/volume* ratio. The area and volume are easy to understand for an open tank without aeration devices. The volume is then the tank volume and the area is the contact area between water and air. When using aeration devices, the area depends on the bubbles, which are affected by the aeration device and the air flow rate. The contact time between the bubbles and the wastewater is also important. Small bubbles are preferred, since they rise more slowly and hence have longer contact time. Many small bubbles are also better than a few large bubbles because the contact area with the wastewater becomes larger.

There exist models of the oxygen transfer for clean water. These models can be extended to be valid for wastewater. This is done by introducing constants. For example, the K_La for wastewater is found by multiplying the K_La for clean water (K_La_{CW}) by a constant α, where the constant α is defined as

$$\alpha = \frac{K_La}{K_La_{CW}} \tag{5}$$

In the same way, a constant β is included to compensate for the difference in the saturated dissolved oxygen concentration between wastewater y_{sat} and clean water y_{satCW}. The constant β is defined as

$$\beta = \frac{y_{sat}}{y_{satCW}} \tag{6}$$

There exist further extensions of (4) but these will not be considered here. The extensions are also hard to take advantage of, because they contain many unknown constants.

4.2 The dissolved oxygen dynamics

In an activated sludge process, biodegradable matter is degraded by microorganisms which consume oxygen. We will study one section of the aerating basin and treating it as completely mixed, see Figure 6.

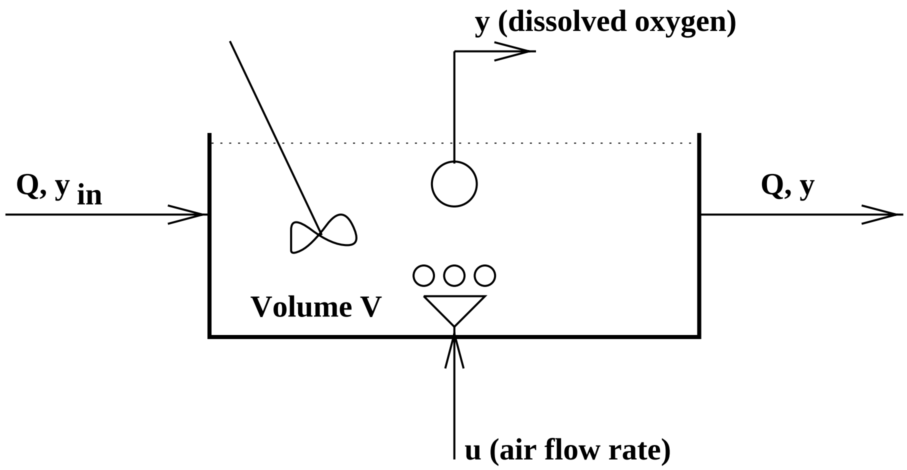

Figure 6: Typical shape of the oxygen transfer function ($K_L a(u)$) as a function of the airflow rate.

A mass balance yields the following dissolved oxygen model

$$\frac{dy(t)}{dt} = \frac{Q(t)}{V}(y_{in}(t) - y(t)) + K_L a(u(t))(y_{sat} - y(t)) - R(t) \tag{7}$$

where

$y(t)$	is the DO concentration in the zone
$y_{in}(t)$	is the DO concentration of the input flow
y_{sat}	is the saturated value of the DO concentration
$Q(t)$	is the wastewater flow rate
V	is the volume of the wastewater
$K_L a(u)$	is the oxygen transfer function, see Figure 7
$u(t)$	is the airflow rate into the zone from the air production system
$R(t)$	is the respiration rate (oxygen utilization rate)

Here, we will assume that $y(t)$, $y_{in}(t)$, $u(t)$ and $Q(t)$ are measured and that y_{sat} and V are known constants.

Equation (7) describes the rate of change in the dissolved oxygen concentration. The first term of the right hand side in (7) is a pure mass balance, influent oxygen – effluent oxygen times the dilution rate (Q/V). The next term ($K_L a(u(t))(y_{sat} - y(t))$) is the addition of oxygen and the last term $R(t)$, describes the oxygen consumption.

The respiration rate $R(t)$ depends on the biomass concentration and describes the oxygen consumption of the microorganisms. The respiration rate is time varying. Typically, it has a daily variation around a nonzero mean value, but it may change abruptly due to disturbances.

The oxygen transfer function $K_L a$ depends nonlinearly on the airflow rate. A typical $K_L a$ function is shown in Figure 7.

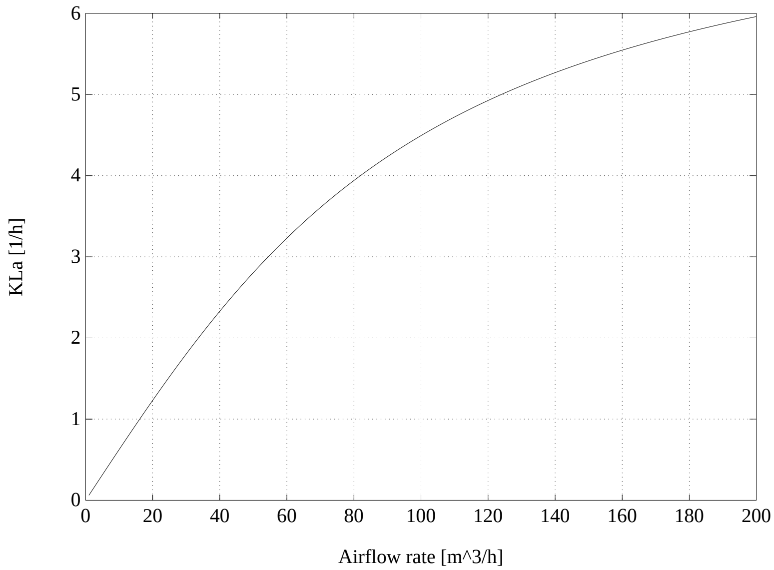

Figure 7: Typical shape of the oxygen transfer function $K_La(u)$ as a function of the air flow rate (u).

4.3 The control problem

The gain of the DO process varies with respect to the airflow rate due to the nonlinear K_La function, see Figure 7. This may cause problems when using a linear controller. In Figure 8 such a problem is illustrated, where a linear PI-controller is tuned for high performance during a high airflow rate but used for a low airflow rate. This will be the case if the controller is tuned during a high load (respiration rate). When the airflow rate decreases (due to a lower load), the process gain[1] increases, and the system starts to oscillate.

If instead, the linear PI controller was tuned for a high performance during a low load, a slow closed loop system would be obtained for a high load, which hence rejects load disturbances slowly.

By taking the nonlinear K_La into account, a fair step response for all loads is, however, possible to achieve. How this can be done will be described in the the following sections.

4.4 The nonlinear DO controller

There has been extensive research in different linear control design methods for linear systems. Hence, there exist many high performance control strategies for linear systems. The DO process is, however, not a linear system.

$$\frac{dy(t)}{dt} = \frac{Q(t)}{V}(y_{in}(t) - y(t)) + K_La(u(t))(y_{sat} - y(t)) - R(t) \tag{8}$$

where the different variables are defined above. The DO dynamics in (8) may be linearized by introducing a variable $x(t)$, defined as

$$x(t) = K_La(u(t))(y_{sat} - y(t)) \tag{9}$$

[1] The derivative of K_La.

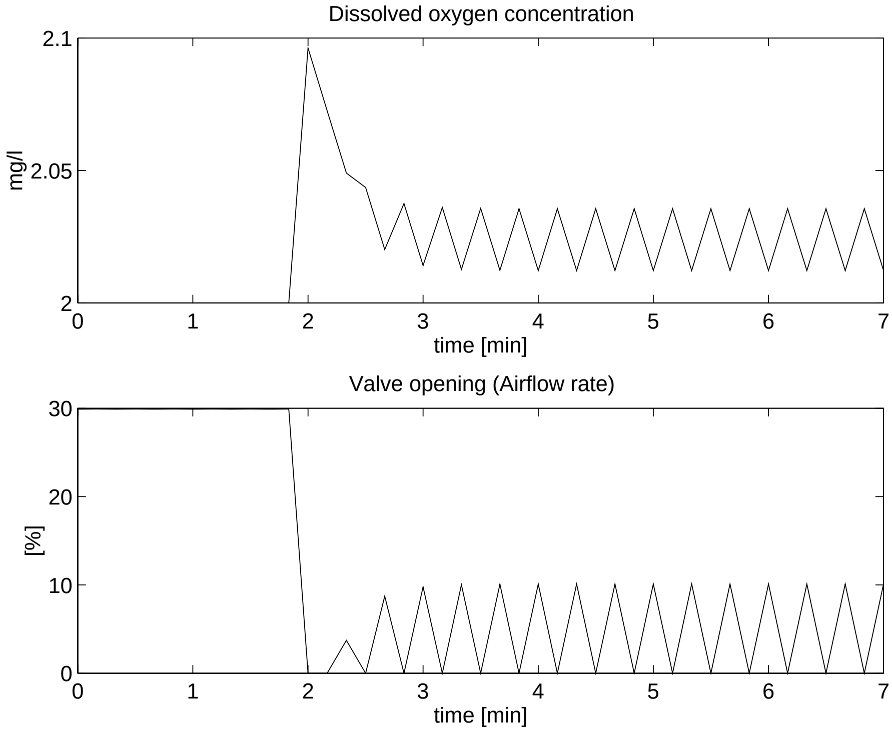

Figure 8: The DO and airflow rate for a step disturbance in the respiration rate during a low load (respiration rate) when controlled by a linear PI-regulator which is tuned for a high load.

The control signal $u(t)$ is calculated by using the inverse of K_La function[2]. This approach is called *exact linearization*. Equation (9) gives

$$u(t) = K_L^{-1}a(\frac{x(t)}{y_{sat} - y(t)}) \tag{10}$$

A typical model for K_La is an exponential model, $K_La(u(t)) = k_1(1 - e^{-k_2u(t))}$. For this case $u(t)$ is given as

$$u(t) = -\frac{1}{k_2} \ln\left(1 - \frac{x(t)}{k_1(y_{sat} - y(t))}\right) \tag{11}$$

A block diagram of the linearized process is shown in Figure 9.

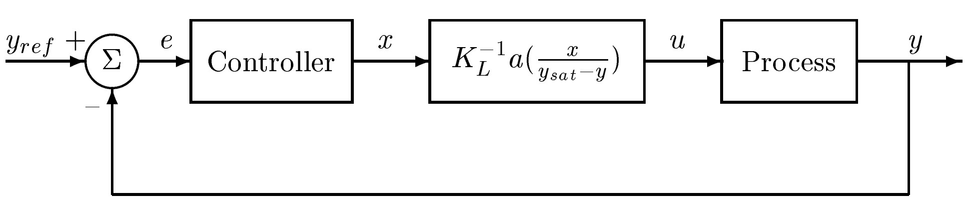

Figure 9: The basic idea with the nonlinear controller.

[2]This linearization requires that the K_La model is invertible.

Inserting (10) in the process model (8) and assuming a *correctly* modeled K_La function gives the linearized process model

$$\frac{dy(t)}{dt} = \frac{Q(t)}{V}(y_{in}(t) - y(t)) + x(t) - R(t) \tag{12}$$

As mentioned before, there exist several control design methods for linear systems which may be applied for the system (12). In the following section, pole-placement with a PI-controller will be applied.

Remark 1: In the above discussions we have neglected the air flow valve characteristics. If the valve characteristics is nonlinear, two approaches are possible:

- Use cascade control, where a local controller is used to control the air flow rate. Obviously, this approach requires the airflow rate to be measured, see further Section 4.8.
- Use a model to compensate for the nonlinear valve characteristics. This can easily be incorporated in the model for the K_La by replacing $K_La(u)$ with $K_La(\phi)$ where ϕ is the air valve positioning

4.5 Pole-placement with a PI-controller*

Pole-placement will here be used to calculate the parameters of a PI-regulator. The controller design is performed in two steps. First the closed loop transfer function is derived, expressed in terms of the controller parameters. Then, the controller parameters are derived from a user specified pole-placement, e.g. a double pole.

The transfer function for a continuous-time PI-regulator is

$$X(s) = K(1 + \frac{1}{T_I s})E(s) \tag{13}$$

where $X(s)$ and $E(s)$ are the Laplace transforms of the controller output and error signal, K is the proportional gain and T_I is the integration time. The error signal is defined as

$$e(t) = y_{ref}(t) - y(t) \tag{14}$$

By combing the transfer function from $x(t)$ to $y(t)$ in (12) with the controller (13), the closed loop transfer function from $y_{ref}(t)$ to $y(t)$ is found to be

$$G_{CL}(s) = \frac{K(T_I s + 1)}{T_I(s + D)s + K(T_I s + 1)} \tag{15}$$

where $D = Q/V$.

To calculate suitable parameter values for K and T_I, we choose the closed loop poles to be a double pole in $s = -\alpha$. Complex conjugated poles would of course also be possible, but will not be considered here. Comparing the poles of (15) with the desired pole location

$$(s + \alpha)^2 = s^2 + 2\alpha s + \alpha^2 \tag{16}$$

gives two equations, where K and T_I are found to be

$$K = 2\alpha - D \tag{17}$$

$$T_I = \frac{2\alpha - D}{\alpha^2} \tag{18}$$

This method gives an easy way of designing a PI-controller. The user has only to choose one parameter, the pole location α. The pole location approximately trades off control energy and speed. A double pole close to 0 gives a slow controller which is less sensitive to noise and modeling errors, while a pole location far out on the negative real axis gives a closed loop system which is fast but more sensitive to noise and modeling errors.

Remark 1: For implementation of the controller (13) in a computer the control law has to be discretized.

Remark 2: The incoming DO is acting as a disturbance, see Figure 6.
The control strategy can be expanded with feedforward from the incoming DO (y_{in}).

4.6 Illustration of the control strategy

Here, we show how the nonlinear control strategy works in practice. The presented nonlinear PI-controller was tested at a pilot plant in Uppsala and compared to a linear PI-controller.

The experiment was performed in the first aerobic zone in the pilot plant, where the load variations are expected to be the largest and the nonlinear controller might be most useful.

The experiment was started by determine the nonlinear K_La function (which is outside the scope of this presentation)

First we show the performance of the linear controller. The result is shown in Figure 10. As seen, we have acceptable performance when the DO set point is high (high air flow rate) but when the set-point is lowered (the airflow rate is lowered), the behavior deteriorates significantly. The controlled process starts to oscillate for low air flow rates as predicted by the theory.
Next we applied the nonlinear controller which uses a model of K_La. Figure 11 illustrates the performance of the nonlinear controller. As seen, this controller gives a much better result for the low set-point, since the nonlinear controller reduces its gain for low airflow rates.
The nonlinear controller hence has acceptable performance for all working conditions, while the linear controller starts to oscillate for low airflow rates. This illustrates that the DO process actually is nonlinear and a nonlinear controller, also in practice, outperform a linear controller.

Finally, it is important to note that in many cases one may be satisfied with a slow disturbance rejection i.e. a slow controller. Then a linear controller can be used. In practice the tuning is often done empirically or by using data obtained from a step response.

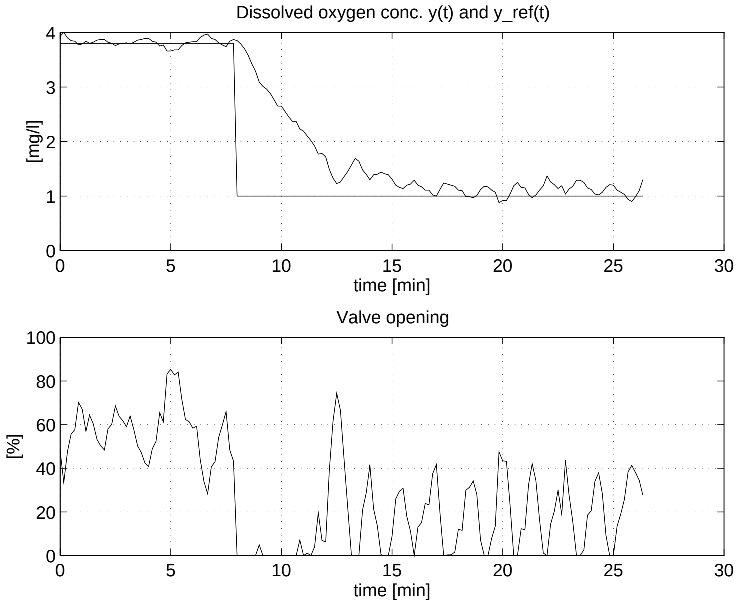

Figure 10: Linear control of the dissolved oxygen concentration.

4.7 Cascade control using air flow rate measurements

Often, it is possible to measure the air flow rate. A cascade control strategy can then be used as illustrated in Figure 12. A secondary (slave) controller is used for the air flow rate. The output signal from the primary (master, supervision) controller becomes the set point for the secondary controller. This strategy decreases the negative effect of a possible nonlinear air valve characteristics and can also more quickly react on flow disturbances.

Cascade control is commonly used for DO control. When tuning the controllers it is advantageous to start with the local controller. Note that the tuning of the DO controller is in general easier when using a secondary controller than when only one controller is used.

4.8 Control of the dissolved oxygen set-point

In the aerobic part of an activated sludge process, ammonium is converted to nitrate by nitrification. The nitrification process requires oxygen, which is obtained by aerating the water. Normally, a constant DO, controlled by varying the airflow rate, guarantees that enough oxygen is supplied to the process. An alternative is to use a *time-varying* set-point of the DO, determined by the ammonium concentration in the last aerobic zone. The basic idea is to control the DO set-point from on-line measurements of the ammonium concentration. This is illustrated in Figure 13. Note that this strategy can be viewed as a cascade control where the DO controller now acts as a local controller.

A DO set-point control may give the following advantages, depending on the existing plant performance:

- Better control of effluent ammonium.
- Lower average DO set-point which saves energy (due to a lower air consumption).

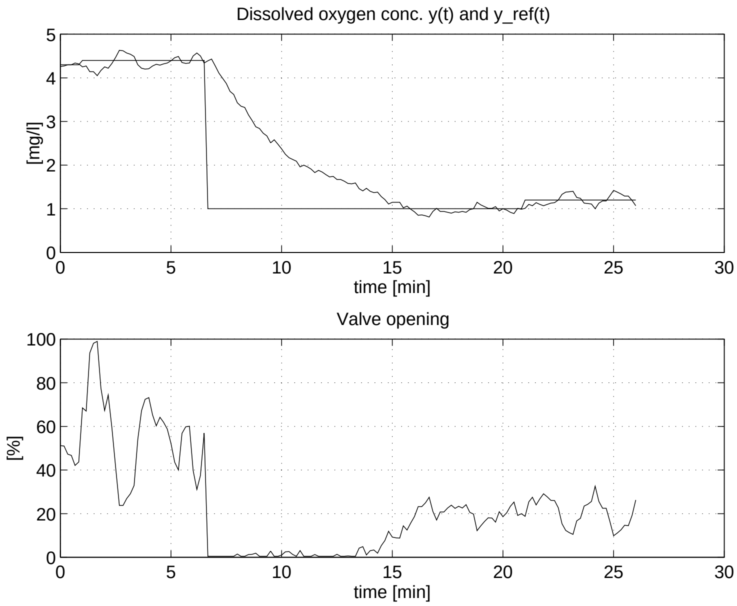

Figure 11: Nonlinear control of the dissolved oxygen concentration

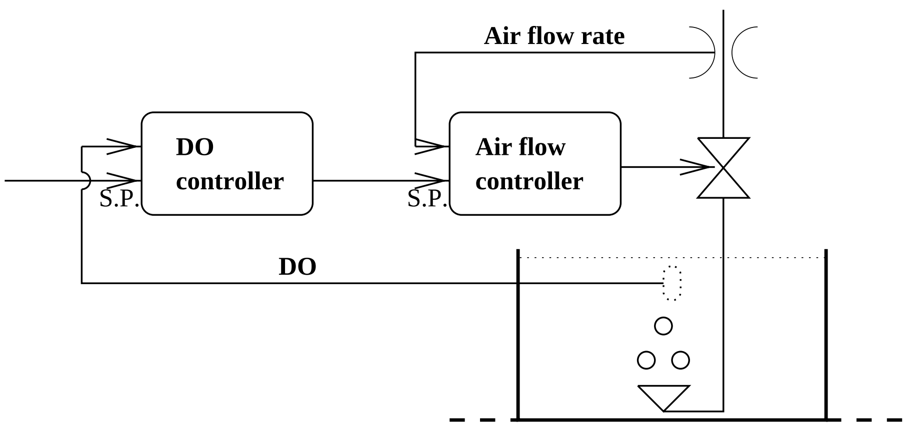

Figure 12: A DO controller with cascade control (S.P.= set point).

- Lower nitrate concentration in the effluent, because of improved denitrification due to a lower DO.
- Lower dosage of external carbon (if it is added).

Possible disadvantages may be that the

- The sludge properties deteriorate
- Risk for increased emission of nitrous oxide (N_2O).
- If a low DO is enough (and hence a low air flow rate) to keep the desired ammonia level, the air flow rate may not mix the sludge sufficiently. The problem can, however, easily be solved by also use mixers.

Another variant of DO set-point control may reduce these problems. When there are several aerated zones, which often is the case, spatial DO control is possible. One idea is to switch on or off aeration in the first or last zone(s) when the ammonia level becomes too high or too low. This latter strategy avoids that the DO becomes low in the whole

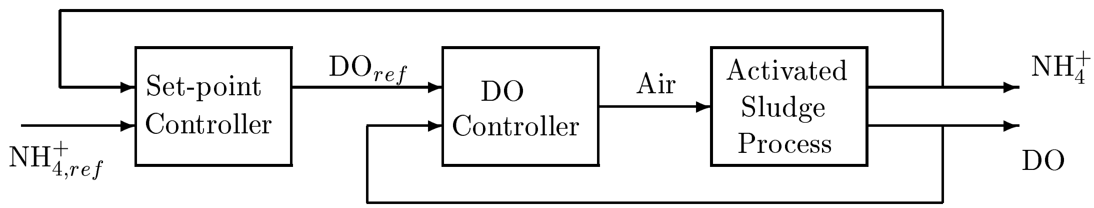

Figure 13: Block diagram of a DO set-point controller

aeration basin, and is probably better than using the same DO set-point in all aerated zones.

4.8.1 A practical experiment

Here, we will illustrate how a DO set-point controller may work in practice. The control strategy was tested at a pilot plant in Uppsala.
For simplicity, the same DO set-point was used in all three aerated zones. The ammonium concentration was measured in the last aerated zone where the highest ammonium concentration is expected to be found, see also Figure 14.

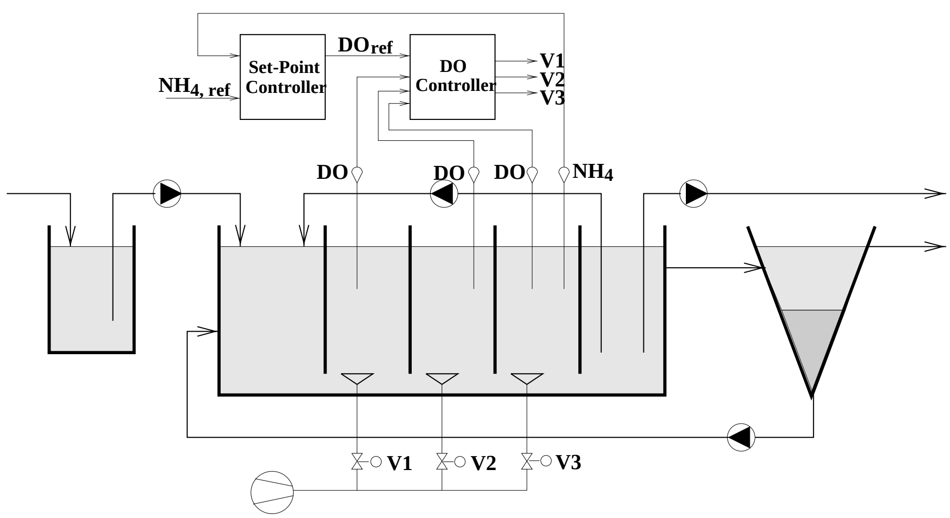

Figure 14: Layout of the plant (line 1) with the sensor placement together with the controller (both controllers were of PI-type).

The set-point controller was started after approximately 1.5 days with a set-point of the ammonium concentration at 1 mg/l. The experiment was made in line 1 while line 2 was used as reference. The set point of ammonium was chosen as 1 mg/l. The experiment is illustrated in Figure 15 and Table 1.

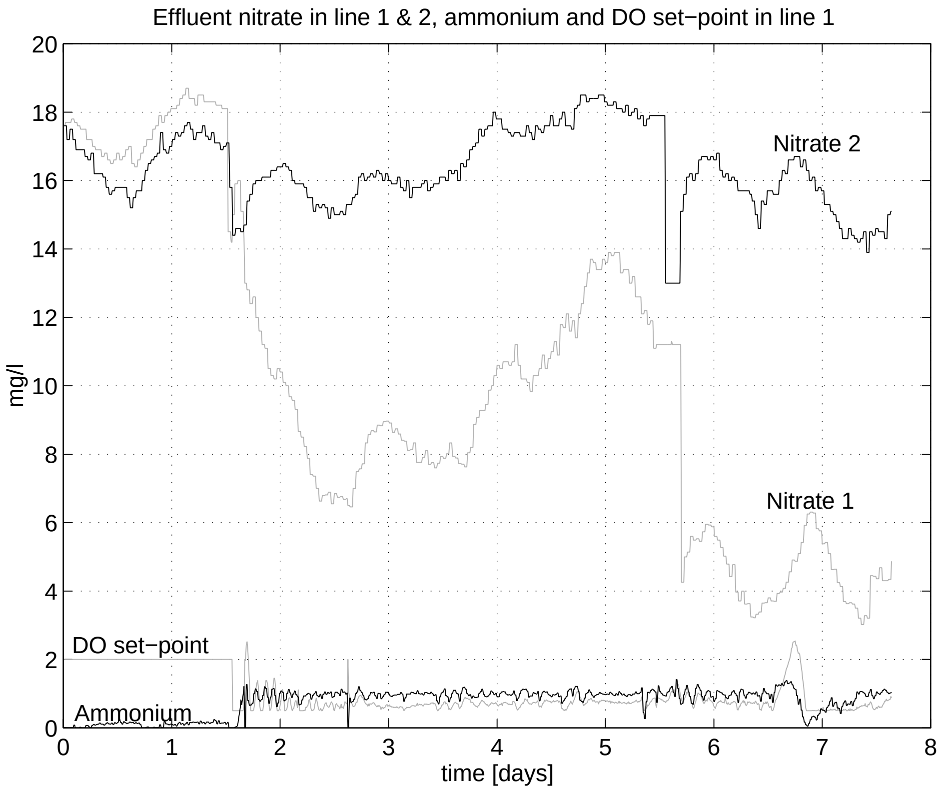

Figure 15: Control of the DO set-point. The control was started after 1.5 days with an ammonium set-point of 1 mg/l. The experiments were made in line 1, line 2 was used as a reference.

	Line P1	Line P2
DO	Controlled	2 mg/l
Ammonium	1 mg/l	0 mg/l
Nitrate	5 mg/l	15 mg/l

Table 1: Results (given as *approximate* mean values during the last 2 days) of DO set point control in line P1, line P2 was used as reference.

Since the ammonium level was lower than the ammonium set-point, the DO set-point was decreased from 2 mg/l to below 1 mg/l. The large abrupt changes in the nitrate concentrations at $t = 1.5$ and $t = 5.5$ in Figure 15 are caused by calibrations of the nitrate sensor. It can be noted that the used DO set-point was not accurately tuned. Both the DO set-point and ammonium concentration sometimes oscillated. These oscillations can be reduced by a better controller tuning.

A positive effect of the lower DO level was that the effluent nitrate level was significantly decreased. Note that the total effluent nitrate level for the controlled line (1) is reduced to less than half. Effluent ammonium was increased from about zero to the set-point of 1 mg/l, but this minor increase should be compared with the large reduction in effluent nitrate.

The significant reduction in nitrate which was found in the experiment described above may not be reached in a more optimized plant. In for example plants with a large anoxic zone, the nitrate reduction will probably not be that large. Also, the composition of the influent carbon may affect the results.

In summary, it can be concluded that the suggested strategy has large potential in terms of energy savings and nitrogen reduction.

4.9 Pressure control

In a DO control system the valve position is normally the control signal. The air flow rate depends on the valve positioning but also on the air pressure in the pipes. It is important to have a sufficient high air pressure before the control valves. Otherwise, even a fully opened valve may not give enough air to the water (ie the actual DO will be less than the set-pint).
A solution to this problem is illustrated in the block diagram in Figure 16. The idea is to measure the valve openings and feedback the most open valve (φ_{max}) to the pressure controller. The controller increases the pressure if $\varphi_{max} > \varphi_{ref}$ and decreases it if $\varphi_{max} < \varphi_{ref}$.

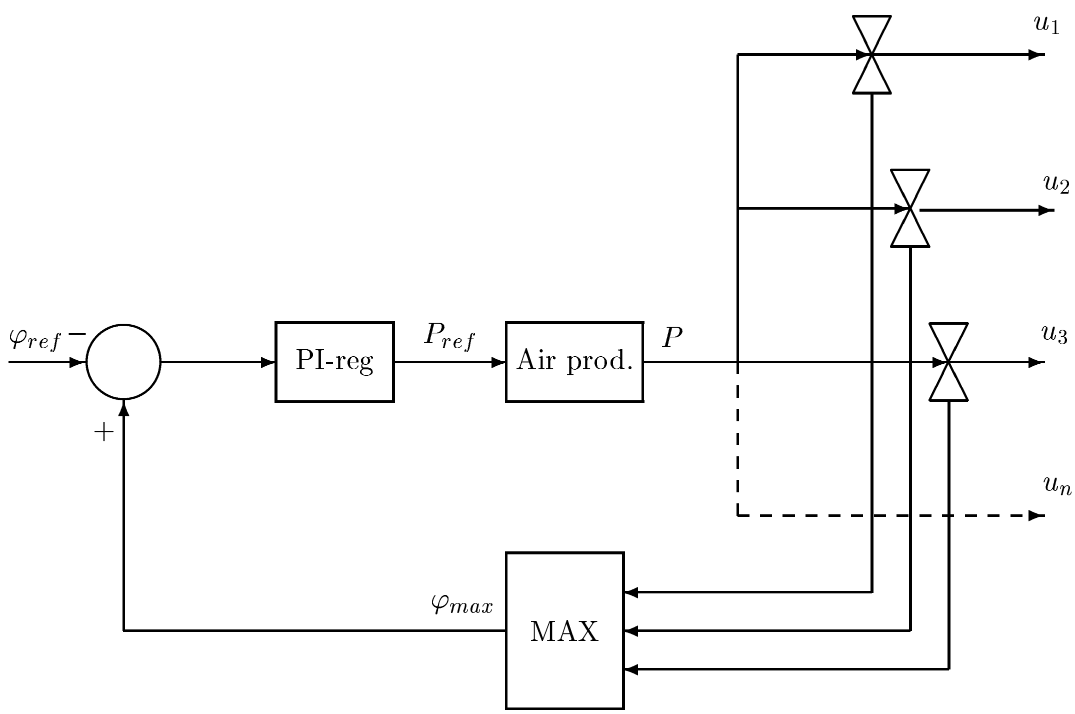

Figure 16: A pressure controller, which adjust the pressure so that the most open valve positioning φ_{max} is equal to a given reference value φ_{ref}. Note that the control error is $\varphi_{max} - \varphi_{ref}$.

To minimize the pressure drop (and hence the energy), the most opened valve should be kept completely open. This is, however, not feasible since then no control authority in the positive direction is obtained. Therefore, φ_{ref} is chosen lower than 100% in practice.

The pressure controller should be made slow to avoid coupling effects between the DO controller and the pressure controller.

5 Control of external carbon flow rate

Here, we give some motivations why it may be important to control the flow rate of external carbon and briefly present a basic control strategy.

5.1 Motivations

Biological nitrogen removal in activated sludge processes is dependent on sufficient supplies of easily metabolized carbon compounds for the denitrifying bacterial population. An external carbon source can increase denitrification rates and compensate for deficiencies in the influent carbon/nitrogen ratio. This works, however, only if the denitrification process is carbon constrained. Possible carbon sources include methanol, ethanol, acetate, primary sludge and various industrial waste products.

It is important to control the flow rate of the external carbon source. A *too low* dosage will leave the denitrification process carbon constrained and the full capacity for nitrogen removal is not used. A *too high* carbon dosage is expensive, may cause carbon spill and increases the sludge production which affects the nitrification capacity. Another potential problem with overdosing is that the microorganisms may lose their capacity to use natural existing carbon sources.

When adding an external carbon source one should be aware that a very selected microbial system may be induced, and it may take weeks for the microorganisms to adapt to the external carbon. It is also of importance to note that reliability problems with on-line nitrate sensors may occur.

A constant flow rate of carbon is only advantageous when the influent variations of the carbon/nitrogen ratio are small. When the variations are large (in a typical plant the load often varies by a factor of 6 or more), a constant carbon dosage will be too low during some hours and too high during other periods. The average nitrate concentration will then not be reduced as much with a constant dosage as it would with a controlled dosage.

If external carbon is added in the last step of a wastewater treatment plant, it is very important to give a correct dosage, since there are no later steps in the plant where an excessive dosage can be degraded.

5.2 A basic strategy

A reasonable strategy for controlling an external carbon flow rate is to keep the nitrate level in the last anoxic zone at a constant low level, see Figure 17.

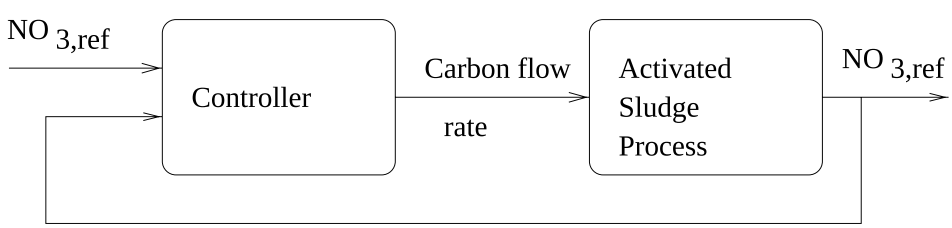

Figure 17: A basic block diagram for carbon flow rate control. The flow rate is normally feed into the first anoxic zone and the nitrate to be controlled is measured at the end of the last anoxic zone.

In a pre-dentrifying plant, this strategy is depicted in Figure 18. Several control algorithms and tuning procedures are possible, as well as, extending the controller with feedforward. For example, if the incoming organic load can be measured this information may be used as a feedforward signal to the controller (if the incoming organic matter increases the flow rate of external carbon should be decreased).

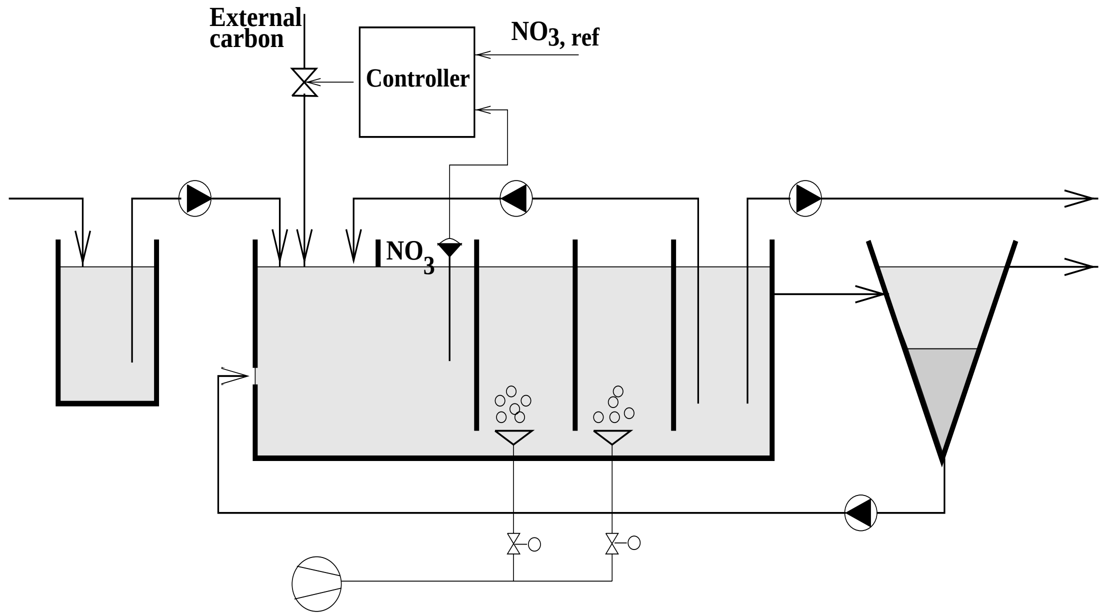

Figure 18: Control of an external carbon source in an pre-denitrifying activated sludge plant.