Solids management for the control of extended aeration systems: An analysis of classical and advanced strategies

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Abstract

This paper initially presents a detailed critical assessment of the conventional methods for solids management in the activated sludge process, with a particular view to extended aeration systems. The following control strategies are analysed:

- control of process indicators: sludge loading (F/M), sludge age and oxygen utilisation rate (OUR),
- control of MLSS and sludge mass and
- control based on the clarifier behaviour.

The main limitations of these strategies are discussed, namely the incapacity of covering on an integrated basis the dynamic state of the system, the interactions between the reactor and the final clarifier and the various process variables involved. In order to address the above limitations, 2 control strategies developed by the author based on an integrated and optimal approach to the system are described. The first strategy comprises the optimal control of the process (effluent quality and operating costs), while the second strategy is a rule-based control. A comparison, using Monte Carlo simulations, between the 2 proposed strategies and some of the conventional strategies indicated the 2 strategies to be superior to the conventional ones in terms of cost-benefit.

Nomenclature

ARIMA = auto-regressive integrated moving average model
BOD = biochemical oxygen demand
COD = chemical oxygen demand
DO = dissolved oxygen
F/M = food-to-micro-organism ratio
K_La = overall oxygen mass transfer coefficient
MCRT = mean cell residence time
MLSS = mixed liquor suspended solids
OUR = oxygen utilisation rate
Qr = return sludge flow
Q_w = waste sludge flow
R = recycle ratio
RASS = return activated sludge suspended solids
SCOUR = specific carbonaceous oxygen utilisation rate
SNOUR = specific nitrogenous oxygen utilisation rate
SRT = solids retention time
SS = suspended solids
$SSVI_{3,5}$ = stirred sludge volume index at a concentration of 3,5 *g/ℓ*
STOUR = specific total oxygen utilisation rate
SUR = substrate utilisation rate
SVI = sludge volume index

Introduction

Among the many variants of the activated sludge process for waste-water treatment, extended aeration is probably the most used. Its behaviour is a direct function of the large mass of solids kept in the system and the long residence time of these solids. The particular features of extended aeration systems, which result from these 2 characteristics, are:

- low effluent soluble BOD;
- significant aerobic stabilisation of the sludge;
- high oxygen consumption for biomass respiration;
- low production of surplus sludge;
- potential for achieving nitrification at all times;
- great damping capacity and resistance to shock loads;
- high energy consumption per unit BOD oxidised; and
- conceptual simplicity (primary sedimentation not necessary, only one type of sludge to be handled, sludge stabilisation within the reactor).

Because extended aeration systems have been traditionally considered to be inherently efficient, there has not been additional motivation for efforts towards performance improvement. However, due to the fact that in many cases extended aeration systems operate virtually unattended, eventual process failures may even remain unnoticed, and no change in the operating mode is thus regarded as justifiable.

Two of the most common failures are not caused by exogenous sources, but are mainly a product of an internal overloading of the system, brought about by an excessive mass of solids in the reactor or final clarifier. The first example is the loss of nitrification due to lack of dissolved oxygen, which is frequently due to high MLSS levels causing a high oxygen consumption for biomass respiration. The second frequent failure is high effluent suspended solids (and the associated particulate BOD) as a result of final clarifier overloading, again frequently caused by high MLSS levels.

Other important aspects related to the solids in the system are the high energy consumption for aeration, and the production of relatively small quantities of excess sludge. The balance between a higher energy cost and lower sludge handling and disposal costs is site-specific, and there is no general rule to bring about the lowest overall cost.

Because the performance and costs of extended aeration plants are essentially dominated by the solids in the system, the control of the process has to be directed towards their management. The

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objective of this paper is to present a critical analysis of the most frequently used approaches and the new trends for solids management in the activated sludge process, focused on their applicability for the control of extended aeration systems.

The 2 variables that can be used to control the solids in the system are the return sludge flow (Q_r) and the waste sludge flow (Q_w), herein called manipulated variables. The variables which are objects of the control action are designated control variables. These are basically the process state variables (e.g. MLSS, sludge blanket height), which also include the effluent concentrations (output variables, such as effluent suspended solids, BOD and ammonia). Finally, the variables that drive the system and cannot be directly controlled are the input variables, in this case the influent flow and concentrations (e.g. suspended solids, BOD and ammonia).

The paper initially presents a critical analysis of the control strategies conventionally used for the control of the activated sludge process. These are:

- the control of process indicators;
- control of the MLSS concentration and the sludge mass in the system; and
- control based on the clarifier behaviour.

After a general discussion of their main aspects, 2 more advanced strategies based specifically on extended aeration systems are proposed. A comparison of the performance of the main strategies under a large number of different scenarios (Monte Carlo simulation) is undertaken, giving support to the final conclusions presented.

Control of process indicators

The activated sludge process can be controlled through parameters which are derived indicators or regulators of process performance, not necessarily being a direct representation of effluent quality. This section covers 3 such process indicators, the first 2 being among the most frequently used in the control of activated sludge systems:

- sludge loading (F/M ratio);
- sludge age or solids retention time (SRT); and
- oxygen utilisation rate (OUR).

Control of the sludge loading

The sludge loading, or F/M ratio, is a widely used design parameter, representing the load of substrate per unit sludge mass. Sludge loading is sometimes referred to as the SUR, which differs from F/M in that F/M represents the applied load, and SUR the removed load (equal to F/M times the efficiency of substrate removal).

The control objective is usually to keep F/M constant in order to guarantee a uniform substrate removal. The set point for F/M is usually a design parameter, but it is often adjusted by experience during operation. The procedure for F/M control is normally to adjust the MLSS concentration (by manipulation of Q_w or Q_r) according to the influent substrate load, so that the F/M ratio remains constant.

Control of the process by the F/M ratio has the following advantages (Walker, 1971):

- good effluent quality can in general be achieved; and
- the sludge produced has consistent settling characteristics.

However, the following disadvantages also apply:

- Intensive laboratory work is required in order to measure influent BOD_5 or COD frequently or continuously (Benefield et al., 1975).
- The lag associated with the measurement of BOD_5 represents an obstacle for control (Chandra et al., 1987).
- The unit d^{-1} may be confusing for some operators, when interpreting F/M values (Stall and Sherrard, 1978).
- There is a lack of standardisation of the variables used for determining F/M. Substrate can be expressed as BOD_5 or COD, and biomass can be represented by total solids, volatile solids or active solids (Marais and Ekama, 1976).
- F/M ratio is essentially a steady-state parameter, and its association with effluent quality is not valid under dynamic conditions. Therefore, F/M ratio has limited value for process control in a dynamic environment (Stenstrom and Andrews, 1979).

Regarding the specific utilisation of F/M for the control of extended aeration systems, there are also the following points:

- If the possibilities of instantaneous F/M control using Q_r to cause fast changes in MLSS levels are limited in conventional activated sludge systems (Cashion et al., 1977; Holmberg, 1982), they are even more restricted in extended aeration systems, due to the larger reactor volumes. Additionally, manipulation of Q_w produces effects only in the medium term, being therefore also unable to cope with transient and diurnal variations of substrate loading.
- SUR can be quantitatively related to effluent quality only in terms of soluble substrate. As mentioned, one of the main effluent quality problems in extended aeration systems is the particulate BOD, caused by suspended solids escaping in the effluent. In extended aeration systems the soluble BOD is virtually always low, even under widely varying operating conditions (Von Sperling and Lumbers, 1989). With respect to sludge settleability, there are ranges of SUR where the SVI is lower (James and Elliot, 1984), but there is no quantitative relationship for expressing this association.
- Increases in MLSS in order to keep F/M constant can result in increased solids load to the clarifiers, with possible deterioration of the effluent particulate BOD.

These considerations lead to the conclusion that management of solids based on F/M ratio alone does not guarantee overall good effluent quality.

Control of the solids retention time

Solids retention time (SRT), mean cell residence time (MCRT) or sludge age are normally used interchangeably to express the average time a biological cell remains in the system. At steady state, the net growth of cells is balanced by sludge wastage, so that biomass concentration remains constant. Under these conditions (in which biomass production is equal to wastage), sludge age can also be defined as:

$$\text{SRT} = \frac{\text{mass of solids in the system}}{\text{mass of solids produced per day}} = \frac{\text{mass of solids in the system}}{\text{mass of solids wasted per day}} \qquad (1)$$

Different definitions exist, depending on whether only the mass of solids in the aeration tank is computed (most common approach), or the total mass in the system (aeration tank and clarifiers) is considered.

At steady-state conditions the solids retention time, the SUR and the effluent substrate concentration are related. Even though SRT and F/M (or SUR) are functionally related, the methods used for their control are different. F/M control can make use of Q_r, Q_w and sludge storage, whilst control of SRT is restricted to manipulation of Q_w (Lohmann and Schlegel, 1981). There are 2 classical ways of controlling the solids retention time, with the objective of keeping its value constant:

- Wastage of solids from the return sludge line (concentration of waste sludge equal to RASS). The amount of waste solids is, for a given sludge age, a function of MLSS and RASS. This method produces a thicker waste activated sludge.
- Wastage of solids from the aeration tank or its effluent line (concentration of waste sludge equal to MLSS). This method is called hydraulic control (Garrett, 1958). A fraction of the reactor volume equal to the reciprocal of the sludge age must be wasted every day.

A crucial point must, however, be made about SRT control, which is also applicable to F/M control. Both variables have been derived for steady-state conditions, and it is argued by many authors that they should not be used for the control of dynamic environments, which is essentially the case with activated sludge plants (Stenstrom and Andrews, 1979; Jowitt and Cook, 1983; Vaccari and Christodoulatos, 1989). Sludge age and sludge growth are directly related to organism growth and substrate removal only under steady-state conditions. Under dynamic conditions there are mass accumulations in the reactor (sludge production different from sludge wastage in Eq.1). These mass accumulations are not taken into account in the formulations of SRT and F/M, and can introduce considerable errors (Stenstrom and Andrews, 1979). Under the steady-state assumption no transient conditions are considered, and a sudden increase in influent substrate is assumed to be immediately followed by an increase in biomass concentration. In reality, however, biomass growth will take time, and until the new steady state is reached, a deterioration in performance will be observed (Haas, 1979).

Automatic control of the solids retention time was investigated by several authors, including Curds (1973), Miura (1981), Tanuma et al. (1981) and Vaccari and Christodoulatos (1989), by simulation and experiments at full-scale plants. The general efficacy obtained varied, making it difficult to evaluate the real applicability of SRT control.

Regarding the specific utilisation of SRT for the control of extended aeration systems, the following comments can also be made:

- SRT control aims basically to produce a good effluent in terms of soluble substrate. Because extended aeration systems are already highly efficient in the removal of soluble organic matter, SRT control is probably not so important in this respect.
- Calculation of SRT may be important in order to assess if the system is operating in the desired range (conventional activated sludge or extended aeration). The main implications would be to provide favourable conditions for nitrification and sludge stabilisation. However, drastic changes in the sludge age would be necessary to move a system from extended aeration into a different range.
- The concept of sludge age and its control has been mainly derived for the removal of carbonaceous matter. The sludge age of the nitrifiers is generally considered to be the same of the heterotroph population, under the assumption of constancy and homogeneity in the mixture. However, this is not necessarily true, especially in the case when environmental conditions are more detrimental to one population than to the other (as in the case of low levels of dissolved oxygen affecting the autotrophs more than the heterotrophs). Generalisation of SRT as an overall control parameter could therefore conceal other important aspects.
- SRT control does not consider the important stage of final clarification and its implications on effluent quality in terms of suspended solids and particulate BOD. Therefore SRT cannot be used as a single parameter for the control of the activated sludge process.

Control of the OUR

Because of the limitations of F/M ratio and sludge age for the control of the activated sludge process, different approaches need to be sought. One process indicator that has been proposed by many researchers and plant operators is the OUR, which can be stated simply as the rate at which micro-organisms consume oxygen in their metabolic processes. The quotient between OUR ($gO_2/m^3 \cdot h$) and the biomass concentration ($gMLSS/m^3$) is defined as the specific OUR, expressed in terms of $gO_2/gMLSS \cdot h$. The OUR can be expressed in terms of SCOUR for oxidation of carbonaceous matter; SNOUR for oxidation of nitrogenous matter; and STOUR for oxidation of both.

The advantages and reasons of using OUR or SCOUR/STOUR as a control variable have been discussed by many workers, including Benefield et al. (1975), Andrews (1977), Stenstrom and Andrews (1979), Young (1981), Duke et al. (1981), Yust et al. (1981; 1984), Novak et al. (1984), Goto and Andrews (1985), Vitasovic and Andrews (1987) and Markantonatos (1988). In summary these include:

- SCOUR reflects changes in influent loading or characteristics;
- SCOUR can be related to the effluent substrate;
- SCOUR can influence the settling properties of the sludge;
- SCOUR can reflect the presence of toxic or inhibitory substances;
- the relationship between SCOUR and the specific growth rate is valid for both dynamic and steady-state conditions;
- SCOUR gives an indication of the activity of the sludge;
- a high constant value of SCOUR can be an indication that substrate removal is far from complete, whereas a constant low value suggests that the removal of organics is complete, that active biomass concentrations are low, or inhibitory conditions are present;
- SCOUR is a good indicator of the stability of biological sludges from aerobic digestion processes;
- OUR represents the instantaneous oxygen demand of the mixed liquor for carrying out the biochemical reactions, therefore being directly linked to the energy requirements for aeration; and
- OUR can be measured or calculated from dissolved oxygen values, on an on-line basis.

However, agreement over the above points and the general usefulness of OUR is not universal. Sherrard (1980) advocates that under most circumstances OUR can be used only as a gross qualitative indicator of process operating conditions, and that only when influent flow and composition are relatively constant, OUR can be used to control the process. Further investigations by him and co-workers in a full-scale plant (Edwards and Sherrard, 1982) and in a laboratory-scale plant (Chandra et al., 1987) indicated that there was no correlation between effluent quality (COD) and OUR or SCOUR, even with OUR changing due to a highly variable influent. Pilot-plant studies carried out by Duggan and Cleasby (1976) also with an influent having a highly varying substrate load resulted in damped values of OUR, and as a consequence OUR was not correlated with influent and effluent loads. A possible cause was attributed to the influence on OUR of the relatively constant biomass respiration. Another important practical aspect regarding the control of OUR is the fact that significant changes in reactor mass cannot be easily brought about by manipulation of the sludge recycle. The constraints are due to limitations in pump capacity or sludge storage in the clarifiers (Andrews, 1977; Haas, 1979; Sherrard, 1980).

In order to specify the desired set point for SCOUR, experimental studies might be necessary, aiming at finding the best value satisfying both objectives of substrate removal and good settling properties (Andrews, 1977; Vitasovic and Andrews, 1987).

Several studies investigated either control of OUR or the information provided by OUR to control the process (Benefield et al., 1975; Haas, 1979; Duke et al., 1981), involving manipulation of Q_r, Q_w or both. However, these studies were based on steady-state formulations and did not take into account the impact of the procedures on clarifier behaviour. Their main objective was to develop a theoretical basis for utilisation of OUR for control, and are thus not substantiated by experimental results or simulations. The dynamic state was investigated by Andrews and co-workers (Andrews et al., 1976; Stenstrom and Andrews, 1979; Vitasovic and Andrews, 1987) and Yust et al. (1981; 1984) in the step-feed configuration, where the possibilities of solids manipulation are higher.

In examining the potential applicability of SCOUR for the control of extended aeration systems, the following points should be considered:

- Because effluent soluble BOD is not a critical variable in extended aeration systems, and since control by SCOUR is primarily associated with removal of soluble substrate, it can then be said that SCOUR is not an important process indicator in extended aeration.
- Control by SCOUR does not take into account the solids balance in the final clarifiers and the resulting effect on effluent suspended solids. SCOUR alone is insufficient for determining the overall effluent quality, in terms of soluble and particulate matters.
- Due to the difficulty in causing fast changes in MLSS, Q_r and Q_w have limited capacity for adjusting SCOUR to desired diurnal patterns.
- In extended aeration systems OUR is dominated by biomass respiration, which is approximately constant during the day. As a consequence, STOUR presents little variations, and the objective of having a small variability can be reasonably achieved without any control.

From the above points, it appears that OUR alone is not a suitable control variable for extended aeration systems, and that different or complementary approaches have to be adopted.

Control of MLSS and sludge mass

Even though MLSS is not a process indicator parameter, like OUR, F/M and SRT, nor an output variable like BOD, SS and ammonia, it is still a variable of vital importance in the overall treatment process. Its behaviour influences directly or indirectly all main state and output variables and performance parameters of the activated sludge process. Because of this, control of MLSS is a strategy extensively used in activated sludge.

In extended aeration systems, due to the larger reactor volumes and solids mass, the relative importance of MLSS is greater, and the motivation for its control should be higher. Biomass respiration is usually the major component in the oxygen consumption in oxidation ditches. MLSS concentration can thus influence dissolved oxygen levels, which in turn affect nitrification. Additionally, MLSS represents the solids load to the final clarifiers, thus affecting sludge settling (effluent SS) and thickening (return and surplus sludge concentrations). In terms of operating costs, MLSS levels have a direct impact on the energy consumption for aeration and an indirect influence on the volume of sludge to be disposed of (through the amount and concentration of surplus sludge) (Von Sperling and Lumbers, 1988, 1989).

The control objective traditionally adopted has been to keep MLSS constant. If an adequate MLSS level is kept, then effluent quality is expected to be good. Possible problems may occur if the influent BOD load increases and, with the mass of solids kept constant, the resulting increase in sludge loading can lead to a deterioration in effluent quality (Walker, 1971; Benefield et al., 1975). However, if the solids levels are such as to withstand increases in influent load, then the impact in effluent soluble substrate will be minimal. This is generally the case with extended aeration systems.

In terms of soluble substrate, at steady-state conditions, controlling the concentration or mass of the mixed liquor by sludge wastage is equivalent to controlling the sludge age and F/M ratio. The significance of control actions based on Q_w or Q_r is (Takase and Miura, 1985):

- Q_w controls the total mass of solids in the system;
- Q_r controls the balance between the mass of solids in the reactor and in the clarifiers.

Therefore, potentially, both manipulated variables are able to affect the mass and concentration of solids in the reactor. The control procedure traditionally used is to have Q_w as the manipulated variable, wasting an amount equal to the net biomass growth each day (Walker, 1971; Benefield et al., 1975). However, this method accepts implicitly the steady-state assumption, and does not take into account biomass changes due to variations in inflow, influent substrate, RASS concentration etc. Under dynamic conditions, the wastage policy should be directed not merely at compensating the growth of biomass, but to keep its concentration constant. Therefore many plant operators adopt the more realistic approach of increasing Q_w when MLSS is higher than desired, and of decreasing it when the opposite occurs. The amount of corrective action to be taken is usually left to the experience of the operator. Wastage can be implemented on a continuous or intermittent basis.

The recycle rate can also be used for the control of MLSS. Common practices are to keep the flow rate Q_r or the recycle ratio R constant (Lohmann and Schlegel, 1981). The first option (constant flow rate) represents a no-control policy, under the assumption that Q_r has only a limited capacity to introduce changes in

MLSS. This strategy does not recognise the importance of manipulating Q_r also for control of the clarifier. The second option (constant recycle ratio) is also frequently adopted, but the selection of the ratio to be used and consequently its influence on MLSS are limited by the sludge storage capacity in the clarifiers (Lohmann and Schlegel, 1981).

The difficulty in setting the desired recycle rate or ratio for achieving MLSS control is due to a self-regulating mechanism in the interaction between the reactor and clarifier. If Q_r increases, MLSS will also increase, due to a shifting of solids from the clarifier to the reactor. However, this increase in Q_r will probably result in a decrease in the concentration of RASS, thus lowering the transfer of solids to the reactor and ultimately limiting the increase in MLSS. A reverse situation will happen if Q_r is reduced (Nelson and Mishra, 1980; Von Sperling and Lumbers, 1988).

Since most of the strategies for MLSS control aim to keep it at a constant value, the selection of the desired set point is of a fundamental importance. Usually the MLSS level is selected so as to provide good effluent quality and settling properties (Benefield et al., 1975; Walker, 1971). Schlegel (1977), however, makes the important comment that a variable set point can be adopted, if a dynamic model of the process is integrated within the solids management.

Classical control theory (feedback/feedforward algorithms) for the automatic control of MLSS has been investigated by many researchers, by simulation and at pilot- and full-scale plants (Nogita et al., 1977; Holmberg and Forsstrom, 1984; Butwell et al., 1989; Hiraoka and Tsumura, 1989). Control theory was also adopted by Tanuma et al. (1981) and Takase and Miura (1985), but in this case the objective was to keep the total sludge mass in the system (aeration tank and final clarifiers) at a constant level. Optimal control of MLSS was also investigated by many researchers, having as objective the minimisation of the variation of MLSS around its steady-state value or a target set point (Angelbeck and Shah Alam, 1975; Shah Alam and Angelbeck, 1976; Cook and Marsili-Libelli, 1981; Kodate et al., 1981; Marsili-Libelli, 1984).

A general evaluation of these studies leads to the following points:

- In many cases, the improvement in effluent quality due to control of MLSS to a constant value was not apparent. It is possible that under some circumstances, and depending on the relative state of stress of the plant, MLSS control can be important in terms of effluent quality, whereas in other cases it may be not so influential.
- A constant MLSS implies a variable solids load to the clarifiers, since the influent flow is usually variable. Depending on the MLSS level, this variability can be detrimental to the performance in terms of effluent suspended solids.
- Nitrification and denitrification were not analysed in any of the studies reported. As already commented, MLSS levels influence both processes, and a set point for MLSS directed towards nitrogen removal is not necessarily the best one for removal of carbonaceous matter.

The 3 points above highlight the difficulty in selecting a suitable set point for MLSS, in which control proves to be justifiable and the operation optimal for all objectives. The MLSS set point is normally selected at the operator's discretion. MLSS concentration varies when the policy aims to control F/M, SRT or OUR, but these approaches have their own limitations. There is no reason why the dynamic models used in many control schemes for MLSS control could also not be used for selection of the best set point. Additionally, investigation of the merits and applicability of a variable set point should be also pursued. Optimality in terms of effluent quality could then be more easily obtained under a wider spectrum of operating conditions.

Control based on clarifier behaviour

Considering the importance of the clarification stage in the overall system performance, it is natural to assume that some control strategies should be also oriented directly towards guaranteeing a good and stable performance of the clarifiers. However, the literature shows a scarcity of studies covering dynamic conditions, probably reflecting the difficulty so far encountered in developing reliable dynamic models of clarifiers.

Steady-state approaches for control, based on the analysis of the batch solids flux curve, have been more commonly adopted. Their main characteristic is the selection of the operating point of MLSS or Q_r, so that failure of clarification (deterioration of solids settlement) or thickening (expansion of sludge blanket) is avoided. Examples of these are given by White (1976), Johnstone et al. (1979), Matsui and Furuya (1980), Keinath (1981), Tsugura et al. (1985), Severin et al., (1985), Severin and Poduska (1985), D'Antonio and Carbone (1987). A dynamic model was used by Busby and Andrews (1975) for the investigation of a feedback control of the sludge blanket height by manipulation of the recycle and surplus sludge flow rates.

In extended aeration plants, the effluent quality is mainly dictated by the presence of suspended solids, what makes the proper consideration of clarifier behaviour essential. From this perspective, it can be said that:

- Manipulation of Q_r and Q_w should be given an special emphasis in guaranteeing a successful operation of the final clarifier.
- Strategies aiming directly at the control of the sludge blanket level seem very attractive.
- The integrated simultaneous manipulation of Q_r and Q_w must be further investigated, since both will have a direct effect in the short and medium term on the mass of solids in the clarifier (Q_r causes changes in a short term - hours, whereas the influence of Q_w can only be felt on medium term - days).

Discussion of the conventional control strategies

A specific discussion of each control strategy was included in the respective sections. A general appraisal of the various points, directed towards their applicability to extended aeration systems, leads to the following main points:

- The vast majority of the strategies described is oriented towards the control of conventional activated sludge systems. Few studies have been devoted to extended aeration processes.
- Among the activated sludge control strategies studied, few integrate the simultaneous control of the reactor and final clarifier, therefore not recognising the importance of their interaction in the overall system performance. Many publications do not consider the impacts of the control actions on clarifier performance.
- Most of the strategies investigate the manipulation of Q_r and Q_w separately, thus not exploring the potential of their integrated management.
- A limited number of strategies consider the implications in terms of operating costs, and only few of them have as

additional objective their reduction.

- In the control strategies based on set points, their values are usually defined somewhat arbitrarily, using vague or non-specified criteria. Analysis of different or variable set points is normally not carried out.
- There is no overall consensus about the variables or process indicators to be used as control signals. All signals suffer from limitations, especially the inability to represent the operation of both the reactor and the clarifier, and also the dual objective of removal of carbonaceous and nitrogenous matter.
- Many studies base their conclusions on a very limited set of data, with an analysis of only 24 h of operation being not uncommon. However, the performance of a control strategy in a highly dynamic environment can of course vary for different situations, which could then lead to different conclusions.

From the above considerations one can be left with the impression that there are no suitable strategies for controlling an extended aeration system, which is, paradoxically, the most reliable version of the activated sludge process. This impression should indeed not be the case, and the point argued here is that an integrated management system should be adopted, instead of the usual approach of controlling the system according to only one variable or process indicator. Even a simple combination of 2 control variables such as MLSS and sludge blanket height is likely to be more successful in terms of overall system performance than any of the isolated approaches, as demonstrated by Von Sperling (1990). Additionally, it is thought that the utilisation of a dynamic model of the overall process can be directly used for deriving and evaluating control strategies. Even if there is still some reluctance to utilise mathematical models, it should be remembered that strategies as simple as the control of the sludge age or F/M ratio have behind them a model (although simple) of the biomass growth and substrate removal kinetics. The proposal of the author is the adoption of a model that, even with a simplified structure, covers both the aeration tank and the final clarifier, and simulates the removal of carbonaceous and nitrogenous matter. The simultaneous consideration of both units and processes is considered the minimum requirement for any control strategy to be adopted for extended aeration systems.

As a summary, the author feels that strategies to be adopted for the control of extended aeration systems should have the following characteristics:

- Integrated management of the system, through (a) simultaneous actuation of the manipulated variables (Q_r and Q_w), (b) appropriate consideration of the interactions of the reactor and clarifiers, (c) consideration of the simultaneous objectives of BOD, SS and ammonia removal and (d) incorporation of cost minimisation as one of the objectives.
- Operation not oriented towards having the control variables matching set points which cannot be clearly specified, but rather towards having the output variables (effluent concentrations) complying to unequivocally set effluent standards (or targets).
- Not using single specific process indicators (e.g. F/M, SRT, OUR) for control, but rather of a dynamic model of the overall system, covering both the reactor and clarifier and with all the relevant input, state and manipulated variables interacting simultaneously. The model (and not a single variable) could then be used to evaluate or to derive the control strategy.

Advanced strategies developed

Advanced strategy based on optimal control

An integrated approach of the optimal management of the extended aeration process addressing the above points was developed by the author (Von Sperling, 1990, 1992; Von Sperling and Lumbers, 1991b) and implemented on a full-scale treatment plant in UK. The procedure is based on the integration of a dynamic process model (reactor and final clarifier) (Von Sperling, 1990; Von Sperling and Lumbers, 1989) with an optimisation algorithm. The optimal management can be set to optimise either effluent quality (with the running costs as constraints) or operating costs (with the effluent quality as constraint). The results obtained by the method are optimal values of the manipulated variables Q_r and Q_w to be adopted during the control horizon. A simplified flow chart is presented in Fig.1. Full details can be found in Von Sperling (1990) and Von Sperling and Lumbers (1991b).

The method is fully integrated in terms of process units (reactor and final clarifier);process variables (input, state and manipulated variables interacting in the dynamic model); and operational objectives (cost and/or performance optimisation).

The dynamic process model covers the oxidation of the carbonaceous and nitrogenous matter in the reactor and the settling and thickening functions in the final clarifier. Since the model was primarily intended for control purposes, all the input variables (inflow, influent suspended solids, influent ammonia), manipulated variables (Q_r, Q_w and optionally K_La) and state variables (MLSS, RASS, DO, sludge blanket height, effluent ammonia and effluent SS) are measurable on a continuous basis. The only exception is the sludge settleability ($SSVI_{3.5}$), which is expressed in the model as a range of values, defining good, fair or poor settleability.

The model structure of the reactor could be simplified by considering the following particular characteristics of extended aeration systems (Von Sperling and Lumbers, 1989):

- Biomass net growth is small and was assumed as constant.
- The kinetics of the removal of soluble BOD need not be modelled (soluble BOD close to zero).
- The rate of oxygen consumption for the oxidation of substrate is expressed as a function of the influent BOD load (itself a function of influent suspended solids).
- The Monod term for inhibition of nitrification by low DO is raised to a power greater than one, in order to increase its sensitivity (loss and recovery of nitrification were observed to be much faster than predicted by a Monod function).

In the final clarifier the sludge zone (variable volume and concentration) was modelled dynamically, using principles of the solids flux theory, and the effluent SS were calculated from an empirical function of the sludge blanket height. The model was calibrated with two-hourly data from a full-scale oxidation ditch (Carrousel system, 50 000 inhabitants) and validated with 4 independent sets of data from 2 other full-scale ditches in the UK (one Carrousel, one conventional Pasveer ditch). Details about the model structure, parameter estimation and simulation results can be found in Von Sperling (1990).

A very important aspect of the proposed control system is that any dynamic model can be incorporated into its algorithm, since the model is external to the optimisation routine. If necessary or justifiable, even a complex model such as the IAWPRC (1987) model can be used. Any further aspects of interest, such as

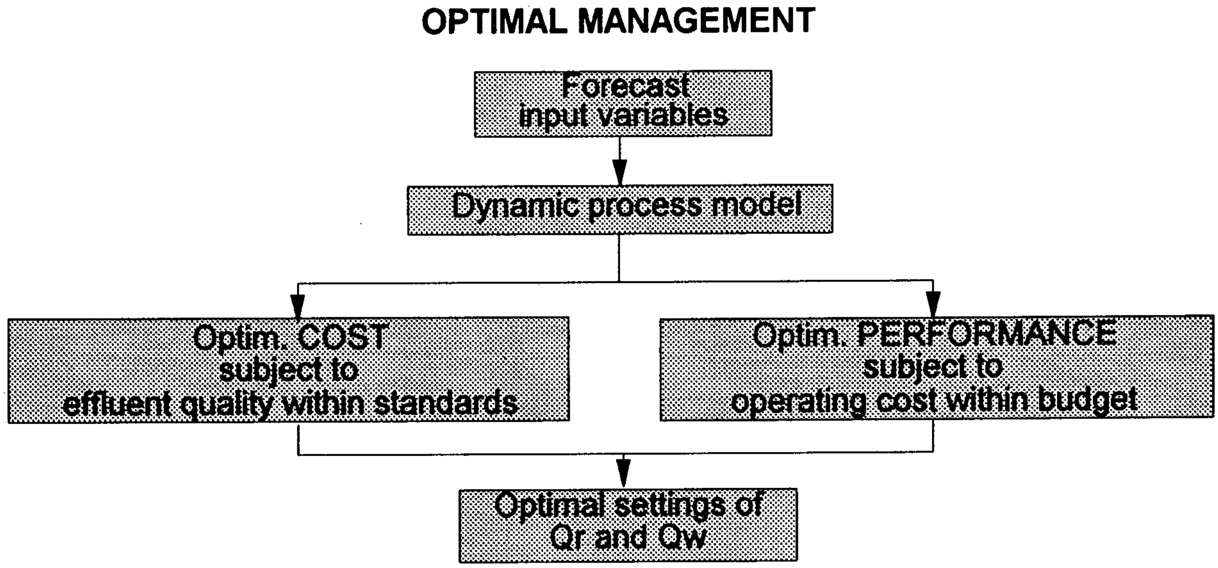

Figure 1
Simplified flow chart of the optimal management strategy

denitrification in final clarifiers or phosphorus removal, if susceptible to modelling, can be included. The major requirements are that the data necessary for driving the model are obtainable in the plant.

The algorithm selected for the optimisation is the Complex method for multivariable non-linear constrained optimisation (Box, 1965). The objective function to be minimised is either the effluent load of ammonia and suspended solids (when optimising performance), or the daily running costs (when optimising costs).

The running costs are calculated based on:

- energy costs for aeration, expressed as power consumption for aeration (kW) times energy costs (pounds/kW);
- energy costs for return sludge pumping, expressed as power consumption for pumping (kW) times energy costs (pounds/kW), and
- transportation costs for land application of thickened sludge, expressed as volume of sludge to be disposed (m^3) times transportation costs (pounds/m^3).

Two types of constraints are incorporated, and the ability to handle both easily is an important feature of the algorithm developed:

- **Explicit constraints**: minimum and maximum values of the manipulated (decision) variables Q_r, Q_w, dictated simply by physical limitations.
- **Implicit constraints**: maximum values of the effluent suspended solids and ammonia concentrations (when optimising costs) or the daily running costs (when optimising performance). The implicit constraints are calculated from the process model, which is integrated within the optimisation algorithm. By doing so, the model can be used in its original form, without any need for transformations or linearisations, which is a limitation from many optimal control strategies. The specification of the implicit constraints related to the effluent quality is straightforward, and is purely a function of the effluent standards. Therefore, there is no need for establishing questionable set points for the state variables (e.g. MLSS) or process indicators (e.g. F/M ratio, sludge age or OUR). The dynamic model calculates the expected effluent quality arising from the combined actuation of all the manipulated variables and the resulting consequences in both the reactor and final clarifier.

There are 2 versions of the optimal control: one for a quasi on-line control, with a horizon of 1 d, and requiring an intensive data collection for the initialisation and utilisation of the control and one at a planning level, with longer horizons, and requiring less data. In both versions it is necessary to forecast the input characteristics for the whole control horizon. In the first version, the forecasting is automated based on ARIMA models, while the second version depends upon the user's decision.

Simplified strategy based on operational rules

It is recognised, however, that even the second version of the optimal control is still relatively intensive in terms of data requirements, especially for small sized treatment plants. Within this perspective, a simplified approach was developed, based on the derivation of operational rules for the system.

Figure 2 presents the flow chart of the stages involved in the derivation of the operational rules. The first step was the undertaking of a series of a large number of simulations (Monte Carlo simulations) using the optimal management strategy. The objective was to obtain the information for building up the knowledge related to the behaviour of the optimal values of the manipulated variables Q_r and Q_w under varying operating conditions. Each run comprised the simulation of one day, with randomly selected values of the input variables and the initial values of the state variables. The total number of runs was 500. In all of them the optimal management strategy was set to minimise costs, having target values for the effluent quality (suspended solids and ammonia) as constraints.

From the results of the Monte Carlo simulation, an analysis of variance of Q_r and Q_w was carried out, in order to determine the

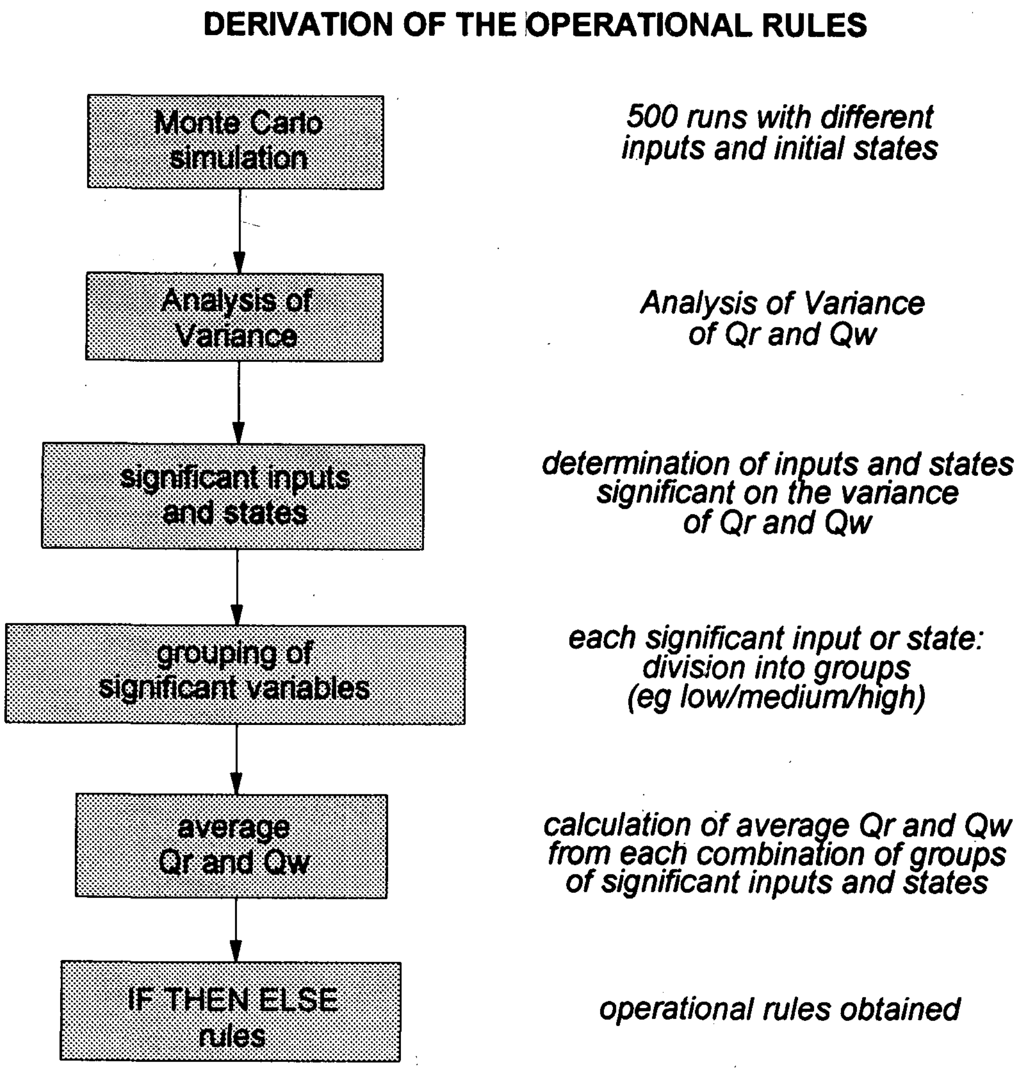

Figure 2
Flow chart of the derivation of the operational rules

inputs and states which were significant. To be coherent with the degree of simplicity required by this operational mode, no continuous measurement of variables was considered to be necessary. Instead, the idea was that the rules should be developed based only on the current value of the significant input and state variables. The horizon was adopted as 24 h, similar to the optimal management strategy. Therefore, only a single measurement of the relevant variables, carried out at the beginning of the operating day, should be necessary for the implementation of the rule-based operation.

After the significant input and state variables had been identified, each of them was divided into 3 groups, which represented low, medium and high values. For each combination of groups representing the conditions of the inputs and states, the average values of Q_r and Q_w were calculated, leading to the formulation of IF-THEN-ELSE rules. An example of one IF-THEN-ELSE rule is (see next page):

TABLE 1
CONTROL STRATEGIES ANALYSED IN THE MONTE CARLO SIMULATIONS

Strategy	Return sludge flow Q_r	Waste sludge flow Q_w
1	Fixed rate (equal to max.)	Fixed rate (equal to max.)
2	Fixed rate (equal to max.)	Control by SRT
3	Feedback with sludge blanket height	Feedback with MLSS concentration
4	Feedback with mass of solids in reactor	Feedback with total solids mass
5	Feedback with sludge blanket height	Feedback with total solids mass

TABLE 2
RESULTS OF THE MONTE CARLO SIMULATIONS

Strategy	Effluent SS			Effluent ammonia-N			Daily average costs (pounds)
	Average (mg/ℓ)	% within target	% within standard	Average (mg/ℓ)	% within target	% within standard	
1	8	100	100	2.8	98	100	343
2	27	70	95	2.4	99	100	223
3	41	70	81	2.4	99	100	228
4	20	84	98	2.5	99	100	262
5	19	85	98	2.5	99	100	262
Optim.COST	22	93	100	2.7	99	100	246
Rule-based	14	99	100	2.9	98	100	286

Obs.:Effluent SS : target = 30 mg/ℓ; standard = 60 mg/ℓ
Effluent ammonia-N: target = 7 mg/ℓ; standard = 20 mg/ℓ

```
"IF   inflow                  between 121 and 190 ℓ/s   AND
      sludge blanket height   between 201 and 210 cm    AND
      MLSS                    between 3 501 and 4 000 mg/ℓ
THEN  $Q_r$ = 193 ℓ/s
ELSE IF inflow                between ...
      ....
      ...
THEN  $Q_r$ = ...
... "
```

With the simple knowledge of the probable range of values of the influent flow, MLSS concentration and the sludge blanket height (all variables easily measurable), the values to be adopted for Q_r and Q_w can be easily obtained from a simple table containing the IF-THEN-ELSE rules. Further details can be found in Von Sperling (1990), Von Sperling and Lumbers (1991a) and Lumbers et al. (1992).

Comparison between the conventional and the advanced control strategies

In order to assess the relative efficacy of the optimal control and the rule-based control compared to other strategies, a series of Monte Carlo simulations was carried out. The reason for using Monte Carlo simulations was to undertake the investigations over a large number of different conditions, generated on a random basis, thus giving a statistical meaning to the results and avoiding drawing conclusions based only on preselected cases. This analysis concentrated on the solids management in the system. Therefore, only Q_r and Q_w were included as manipulated variables, and it was assumed that all alternatives had a perfect DO control (in order to exclude the manipulated variable K_La from the analysis). The simulations were for the Carrousel ditch in the UK (50 000 inhabitants), from which a long series of data was available. The effluent standards in this plant are high (60 mg/ℓ BOD and 20 mg/ℓ ammonia-N), but it should be noted that these values can be easily changed in the optimal control system. Indeed, the constraints set for the optimal control were for target values of the effluent concentrations (30 mg/ℓ BOD and 7 mg/ℓ ammonia-N), and not the standards themselves. The control strategies analysed are presented in Table 1.

The feedback was of a simple type (proportional feedback), with a control interval of 24 h, thus compatible with the planning horizon of the optimal management. The values of the set points and proportional coefficients were mostly obtained by trial and error, with the values selected leading to good and stable performances. Additional details can be found in Von Sperling (1990). The controls by SRT and total solids mass are based on the total mass of suspended solids in the reactor and final clarifier.

The results from 100 runs of 20 d each, varying the input variables and the initial values of the states, are presented in Table 2. Other analyses were carried out, varying the number of days in the simulation, the effluent quality constraints and the amplitude of the variability of the random component, all of them leading to similar conclusions. The results from these other analyses can be found in Von Sperling (1990).

The immediate impression is that the rule-based operation was generally able to provide a better effluent quality in terms of suspended solids (effluent ammonia was similar in all strategies, since nitrification was not a problem in the treatment plant studied, provided MLSS levels were not excessive). The exception was Strategy 1, which led to lower values of effluent SS, but at much higher operating costs, and only a marginal improvement in the percentage of two-hourly samples satisfying the target values. The costs resulting from the rule-based operation were in general higher than those from the other conventional alternatives, but the relative improvement in effluent quality was substantial, especially in the percentage of values within the target. The optimal control strategy also provided a very good overall performance, combined with operating costs lower than those from the rule-based control. The aim of the optimal control when optimising costs is to produce the cheapest operation still satisfying the targets. For this, the effluent concentrations are purposely very close to the target, thus resulting in an economical operation, but not necessarily the best performance in absolute terms. The essence of these conclusions was further reinforced by a statistical analysis based on the matched-pairs hypothesis test (Von Sperling, 1990).

Discussion and conclusions

A general discussion on the conventional control strategies used for the solids management of extended aeration systems was already presented earlier in the paper. The final remarks now address the 2 strategies proposed by the author, analysed in the overall context of solids management.

Optimal control

- The method is fully integrated in terms of process units (reactor and clarifier), process variables (input, manipulated and state variables), performance objectives (output variables and consent targets/standards) and operating objectives (effluent quality and operating costs).
- The method allows flexibility in the definition of its objectives: the operation can be directed towards the optimisation of costs and performance, and the associated constraints (operating targets) can be easily modified.
- The requirements in terms of instrumentation for measurement of the input, manipulated and state variables are intensive. However, if the optimal management is used at an off-line planning mode, hardware requirements are substantially reduced.
- The effectiveness of the proposed optimal management strategy is dependent upon the quality of the forecasting of the input variables. The forecasting method adopted in the study can be improved if additional data of different nature (e.g. rainfall data) are incorporated into the model.
- Compared to other conventional control strategies, the optimal management was, in general, able to give a significantly better effluent quality. However, in some cases this incurred in higher operating costs.

Rule-based control

- The main advantages of the proposed rule-based operation lie in its conceptual simplicity and very limited hardware requirements, since only an indication of the likely range of the current values of inflow, MLSS and sludge blanket level is necessary. The strategy can be simply applied after consulting a table.
- The main weaknesses are a result of the inherent simplicity of the method: relative lack of flexibility, especially when there are factors outside the domain in which the rules were derived, and forced over-simplification in converting the operation of a complex system into a set of simple static rules.
- A comparison of the rule-based operation with the other control strategies via Monte Carlo simulation indicated that the former was able to produce a significantly better effluent in most of the cases. The better effluent quality was however reflected in the operating costs, which were in practically all situations higher than those of the other alternatives.
- The above points (simplicity, reduced hardware requirements, low capital costs and good effluent quality) indicate that the rule-based operation is especially appropriate for small treatment plants. The higher operating costs probably will not be, in this case, so important in terms of absolute values.
- The principle of knowledge acquisition and derivation of a rule-based decision scheme via Monte Carlo simulations using the integrated concept of a model of the system and an optimisation algorithm has been shown to be an efficient procedure. Different operating conditions can be tested, and the rules can be made as general or detailed and as stringent or relaxed as desired. For small treatment works this is a logical procedure, with the intensive data collection and use of the optimiser being done only during the development stage of the knowledge base.
- It is of course clear that the operational rules derived are specific to the treatment plant studied and assume that the model adequately describes actual performance. For a different system, additional investigations would have to be carried out, including data collection, adaptation of the model to the physical configuration of the plant, establishment of specific constraints and cost functions for the optimiser and running of a new series of Monte Carlo simulations. However, the basic concept of the derivation of the rules remains the same.
- The results obtained highlighted the importance of implementing operational control at extended aeration plants. The traditional concept that extended aeration systems should by definition require little operational attention should be re-evaluated, in order to include the need of assessing the relative benefits to be obtained by implementing operational control, in terms of a more efficient and cost-effective performance.

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References

ANDREWS, JF (1977) Specific oxygen utilization rate for control of the activated sludge process. *Prog. Water Technol.* **8** (6) 451-460.

ANDREWS, JF, STENSTROM, M and BUHR, HO (1976) Control systems for the reduction of effluent variability from the activated sludge process. *Prog. Water Technol.* **8** (1) 41-68.

ANGELBECK, DI and SHAH ALAM, AB (1975) Simulation of optimal control strategies in a dynamic continuous flow activated sludge system. *Proc. 30th Ind. Waste Conf.*, Purdue Univ., 159-170.

BENEFIELD, LD, RANDALL, CW and KING, PH (1975) Process control by oxygen-uptake and solids analysis. *J. Water Pollut. Control Fed.* **47** (10) 2498-2503.

BOX, MJ (1965) A new method of constrained optimization and a comparison with other methods. *Computer Journal* **8** (1) 42-52.

BUSBY, JB and ANDREWS, JF (1975) Dynamic modelling and control strategies for the activated sludge process. *J. Water Pollut. Control Fed.* **47** (5) 1055-1080.

BUTWELL, AJ, BURNS, JM, FIELDEN, RS and BERRY, MJ (1989) The application of ICA in sewage treatment - Witney Evaluation and Demonstration Facility (EDF). *Water Sci. Technol.* **21** 1239-1248.

CASHION, BS, KEINATH, TM and SCHUK, WW (1977) Evaluation of instantaneous F/M control strategies for the activated sludge process. *Prog. Water Technol.* **9** (5/6) 593-598.

CHANDRA, S, MINES, RO and SHERRARD, JH (1987) Evaluation of oxygen uptake rate as an activated sludge process control parameter. *J. Water Pollut. Control Fed.* **59** (12) 1009-1016.

COOK, S and MARSILI-LIBELLI, S (1981) Estimation and control problems in activated sludge processes. *Water Sci. Technol.* **13** 737-742.

CURDS, CR (1973) A theoretical study of factors influencing the microbial population dynamics of the activated-sludge process - II. A computer-simulation study to compare two methods of plant operation. *Water Res.* 7 1439-1452.

D'ANTONIO, G and CARBONE, P (1977) Activated sludge process control by behaviour of secondary settling tanks. *Water Sci. Technol.* **19** 1207-1210.

DUGGAN, JB and CLEASBY, JL (1976) Effect of variable loading on oxygen uptake. *J. Water Pollut. Control Fed.* **48** (3) 540-550.

DUKE, ML, ECKENFELDER, WW and TEMPLETON, ME (1981) Strategies for the control of activated sludge plants treating industrial wastewaters. *Water Sci. Technol.* **13** 553-559.

EDWARDS, GL and SHERRARD, JH (1982) Measurement and validity of oxygen uptake as an activated sludge process control parameter. *J. Water Pollut. Control Fed.* **54** (12) 1546, 1552.

GARRETT, MT (Jr.) (1958) Hydraulic control of activated sludge growth rate. *Sewage Ind. Wastes* **30** (3) 253-261.

GOTO, M and ANDREWS, JF (1985) On-line estimation of oxygen uptake rate in the activated sludge process. In: *Instrumentation and Control of Water and Wastewater Treatment and Transport Systems,* Proc. 4th IAWPRC Workshop, Houston & Denver, 465-472.

HAAS, CN (1979) Oxygen uptake rate as an activated sludge control parameter. *J. Water Pollut. Control Fed.* **51** (5) 938-943.

HIRAOKA, M and TSUMURA, K (1989) System identification and control of the activated sludge process by use of a statistical model. *Water Sci. Technol.* **21** 1161-1172.

HOLMBERG, A (1982) Modelling of the activated sludge process for microprocessor-based state estimation and control. *Water Res.* **16** 1233-1246.

HOLMBERG, A and FORSSTROM, J (1984) Application of models in developing control strategies for activated sludge waste water treatment plants. *Water Sci. Technol.* **16** 587-594.

IAWPRC TASK GROUP ON MATHEMATICAL MODELLING FOR DESIGN AND OPERATION OF BIOLOGICAL WASTEWATER TREATMENT (1987) Activated Sludge Model No. 1. IAWPRC Scientific and Technical Reports No. 1.

JAMES, A and ELLIOT, DJ (1984) Activated sludge models. In: JAMES, A (ed.) *An Introduction to Water Quality Modelling.* John Wiley and Sons, 182-196.

JOHNSTONE, DWM, RACHWAL, AJ and HANBURY, MJ (1979) Settlement characteristics and settlement-tank performance in the Carrousel activated sludge system. *Water Pollut. Control* **78** 337-353.

JOWITT, PW and COOK, S (1983) Operational control of oxidation ditches. In: *Energy Savings in Water Pollution Control*, Paris, 26-28 Sept. 1983, 364-379.

KEINATH, TM (1981) Solids inventory control in the activated sludge process. *Water Sci. Technol.* **13** 413-419.

KODATE, H, NAKAYAMA, R and SHIMIZU, T (1981) An algorithm on optimal operations of activated sludge systems. *Water Sci. Technol.* **13** 147-152.

LOHMANN, J and SCHLEGEL, S (1981) Measurement and control of the MLSS concentration in activated sludge plants. *Water Sci. Technol.* **13** 217-224.

LUMBERS, JP, VON SPERLING, M and COOK, SC (1992) Derivation of a rule-based optimal control strategy for the oxidation ditch process using a mathematical model based on field data. *Envirosoft*, UK (in press).

MARAIS, GvR and EKAMA, GA (1976) The activated sludge process. Part I -Steady state behaviour. *Water SA* **2**(4) 164-200.

MARKANTONATOS, P (1988) Modelling for the Operational Control of the Oxidation Ditch Process. Ph.D. Thesis, Imperial College, University of London, London.

MARSILI-LIBELLI, S (1984) Optimal control of the activated sludge process. *Trans. Inst. Measurement & Control* **6** (3) 146-152.

MATSUI, S and FURUYA, N (1980) Activated sludge control in the secondary settling basin using the sludge settling analyser. *Prog. Water Technol.* **12** (3) 213-220.

MIURA, R (1981) An approach to full-automatic control of activated sludge process. *Water Sci. Technol.* **13** 451-457.

NELSON, JK and MISHRA, BB (1980) Digital on-line closed-loop for wastewater treatment operations. *J. Water Pollut. Control Fed.* **52** (2) 406-415.

NOGITA, S, IWAKI, H, OHTO, T and KATO, S (1977) Control experiences of biological solids concentration in a sewage plant. *Prog. Water Technol.* **9** (5/6) 375-379.

NOVAK, JT, EICHELBERGER, MP, BANERJI, SK and YAUN, J (1984) Stabilization of sludge from an oxidation ditch. *J. Water Pollut. Control Fed.* **56** (8) 950-954.

SCHLEGEL, S (1977) Automation of the activated sludge process by oxygen and MLSS control. *Prog. Water Technol.* **9** (5/6) 385-392.

SEVERIN, BF and PODUSKA, RA (1985) Prediction of clarifier sludge blanket failure. *J. Water Pollut. Control Fed.* **57** (4) 285-290.

SEVERIN, BF, PODUSKA, RA, FOGLER, SP and ABRAHAMSEN, TA (1985) Novel uses of steady-state solids flux concepts for on-line clarifier control. In: *Instrumentation and Control of Water and Wastewater Treatment and Transport Systems,* Proc. 4th IAWPRC Workshop, Houston & Denver, 397-404.

SHAH ALAM, AB and ANGELBECK, DI (1976) Optimal control of activated sludge system: laboratory model study. *Proc. 31st Ind. Waste Conf.*, Purdue University, 713-732.

SHERRARD, JH (1980) Communication. Oxygen uptake rate as an activated sludge control parameter. *J. Water Pollut. Control Fed.* **52** (7) 2033-2036.

STALL, TR and SHERRARD, JH (1978) Evaluation of control parameters for the activated sludge process. *J. Water Pollut. Control Fed.* **50** (3) 450-457.

STENSTROM, MK and ANDREWS, JF (1979) Real-time control of activated sludge process. *J. Environ. Eng. Div. ASCE* **105** (EE2) 245-260.

TAKASE, I and MIURA, R (1985) Sludge flow control for activated sludge process. In: *Instrumentation and Control of Water and Wastewater Treatment and Transport Systems*, Proc. 4th IAWPRC Workshop, Houston & Denver, 675-678.

TANUMA, M, KASHIWAGI, M, TUCHIYA, N and KASAI, T (1981) Total sludge quantity control for activated sludge process. *Water Sci. Technol.* **13** 427-432.

TSUGURA, H, SEKINE, T, FUJIMOTO, E and MATSUI, S (1985) Prediction and control of resident sludge in a final clarifier. In: *Instrumentation and Control of Water and Wastewater Treatment and Transport Systems,* Proc. 4th IAWPRC Workshop, Houston & Denver, 653-656.

VACCARI, DA and CHRISTODOULATOS, C (1989) A comparison of several control algorithms for activated sludge waste rate. *Water Sci. Technol.* **21** 1249-1260.

VITASOVIC, Z and ANDREWS, JF (1987) A rule-based control system for the activated sludge process. In: *Systems Analysis in Water Quality Management*, Advances in Water Pollution Control, IAWPRC, Pergamon Press, 423-432.

VON SPERLING, M (1990) Optimal Management of the Oxidation Ditch Process. Ph.D. Thesis, Imperial College, University of London, London.

VON SPERLING, M (1992) Métodos clássicos e avançados para o controle operacional de estações de tratamento de esgotos por aeração prolongada. In: *23rd Interamerican Congress on Sanitary and Environmental Engineering*, Havana, Cuba, 22-26 Nov. 1992.

VON SPERLING, M and LUMBERS, JP (1988) Controle operacional e otimização de custos em sistemas de aeração prolongada. In: *21st Interamerican Congress on Sanitary and Environmental Engineering*, Rio de Janeiro, Brazil, 18-23 Sept. 1988, 171-191.

VON SPERLING, M and LUMBERS, JP (1989) Control objectives and the modelling of MLSS in oxidation ditches. *Water Sci. Technol.* **21** (10/11) 1173-1183.

VON SPERLING, M and LUMBERS, JP (1991a) Operational rules for the optimal management of the oxidation ditch process for wastewater treatment. In: TSAKIRIS, G (ed.) *Advances in Water Resources Technology*, 1991, Balkema, Rotterdam, 387-395.

VON SPERLING, M and LUMBERS, JP (1991b) Optimization of the operation of the oxidation ditch process incorporating a dynamic model. *Water Sci. Technol.* **24** (6) 225-233.

WALKER, LF (1971) Hydraulically controlling solids retention time in the activated sludge process. *J. Water Pollut. Control Fed.* **43** (1) 30-39.

WHITE, MJD (1976) Design and control of secondary settlement tanks. *Water Pollut. Control* **75** 459-467.

YOUNG, JC (1981) Specific oxygen demand as an operating parameter for activated sludge processes. *Water Sci. Technol.* **13** 397-403.

YUST, LJ, STEPHENSON, JP and MURPHY, KL (1981) Dynamic step feed control for organic carbon removal in a suspended growth system. *Water Sci. Technol.* **13** 729-736.

YUST, LJ, STEPHENSON, JP and MURPHY, KL (1984) Control of the specific oxygen utilisation rate for the step-feed activated-sludge process. *Trans. Inst. Measurement & Control* **6** (3) 165-172.