CONTROL STRATEGIES FOR ACTIVATED SLUDGE TREATMENT SYSTEM

By

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Abstract

The activated sludge treatment system for treating municipal wastewater presents an interesting application of system dynamics modeling. This paper presents such a modeling approach to the strategy formulation of the treatment system in order to economically control effluent quality. First, factorial designs are carried out on the simulation results to identify factors that significantly affect effluent quality. Thereafter, open-loop control (both constant and time-varying), output feedback control, and output-integrated feedback control strategies have been applied. Statistical tests of significance indicate that the strategy of output feedback control has the maximum potential, in both summer and winter, to achieve the dual objectives of maintaining effluent quality within acceptable limits and minimizing aerator energy.

Principles Underlying the Activated Sludge Treatment System

The process of Activated Sludge Treatment System (Fig. 1) is the most widely employed technique today it for treatment of municipal wastewater. The influent stream of municipal wastewater, rich in soluble organic compounds (known as substrate or food for the bacteria), enters the reactor (known as aeration tank). Bacteria feed on the organic waste present in the water. Aeration is done by mechanical means providing the much needed oxygen required for the growth of bacteria in the tank.

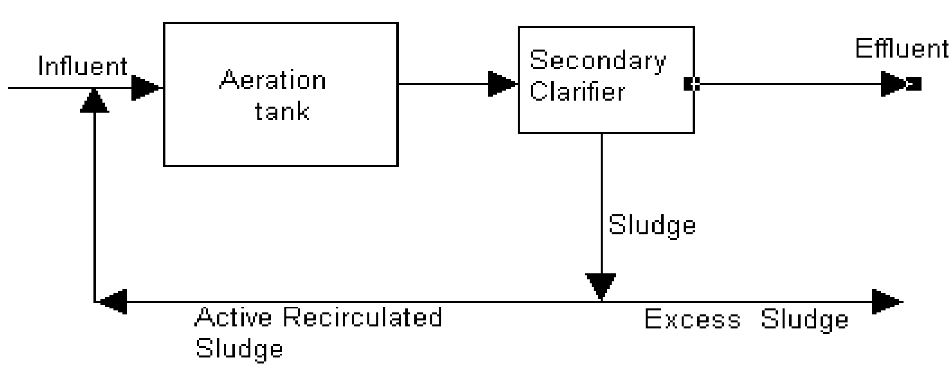


Figure 1: Schematic Diagram of Activated Sludge Treatment System.

The sewage stream loaded with biomass goes out of the aeration tank and reaches the clarifier. The clarifier allows the biomass to flocculate and settle down, due to gravity, as sludge. The sludge contains live biomass. It is re-circulated, in a controlled manner, to the aeration tank so as to maintain the biomass concentration in the tank at a desired level. The excess sludge, which is not re-circulated, is withdrawn from the clarifier and put to sludge drying beds for future use as manures. The clarified supernatant stream goes out of the system as treated effluent.

Researchers have developed a number of models for studying and understanding the wastewater treatment process. These models can be broadly categorized as (1) Component level models and (2) Comprehensive models. Component-level models pertain to sub-areas such as 'substrate removal process' (Novak 1974, Lawrence and McCarty 1974), 'biomass growth process' (Grady and Roper, Jr. 1974, Gaudy, Jr., *et al*. 1974, Grady *et al*. 1986) and Monod 1949), 'oxygen transfer, dissolved oxygen consumption, and oxygen assimilation process' (Bliss and Barnas 1986, Picionreanu, *et al*. 1997), and 'clarification process' (Ford and Eckenfelder 1967).

Comprehensive models pertain to the functioning of the whole treatment system and can be classified as analytical models (Ford and Eckenfelder 1967, Roper, Jr. and Grady, Jr. 1978, Smeers and Tyteca 1984, Uber, *et al.* 1985, Tang, *et al.* 1987, Zhao, *et al.* 1999, and Anderson, *et al.* 2000), simulation models (Busby and Andrews 1975, Barton and Mckeown 1986, and Anderson, *et al.* (2000)), and system dynamics models (Das, *et al.* 1995, 1997 and Clemson, *et al.* 1995).

But for Anderson, *et al.* (2000), none of the studies reported above has designed any control strategy for the output quality exceedences. Clemson, *et al*. (1995) have developed a system dynamics model for wastewater treatment plant and have used Taguchi methods in conducting sensitivity analysis. But their model considers neither the biological process of growth of microorganism nor the process of oxygenation. It also does not try to design a strategy for effluent quality control.

The present work presents a comprehensive system dynamics model for wastewater treatment plant by using the tools, techniques and concepts of design of experiments, statistical quality control, and modern control theory in order to decide the number of aerators to use and design the sludge re-circulation policy while maintaining the effluent quality within acceptable limits.

A Dynamic Model for the Treatment System

Four physical flows can be distinguished in an activated sludge plant: (1) Flow of Liquid, (2) Flow of Biomass, (3) Flow of Substrate or Pollutants, and (4) Flow of Dissolved Oxygen.

Flow of Liquid

Figure 2 is the causal-loop diagram for the flow of liquid. It shows that the inflow to the aeration tank increases the liquid accumulation in the tank and causes an increase in the outflow from the tank (since the tank is always full). This, in turn, decreases the liquid accumulation in the tank. The treated outflow from the tank increases the sludge quantity settled in the clarifier and subsequently increases the clarified effluent quantity, waste sludge quantity, and re-circulated active sludge quantity.

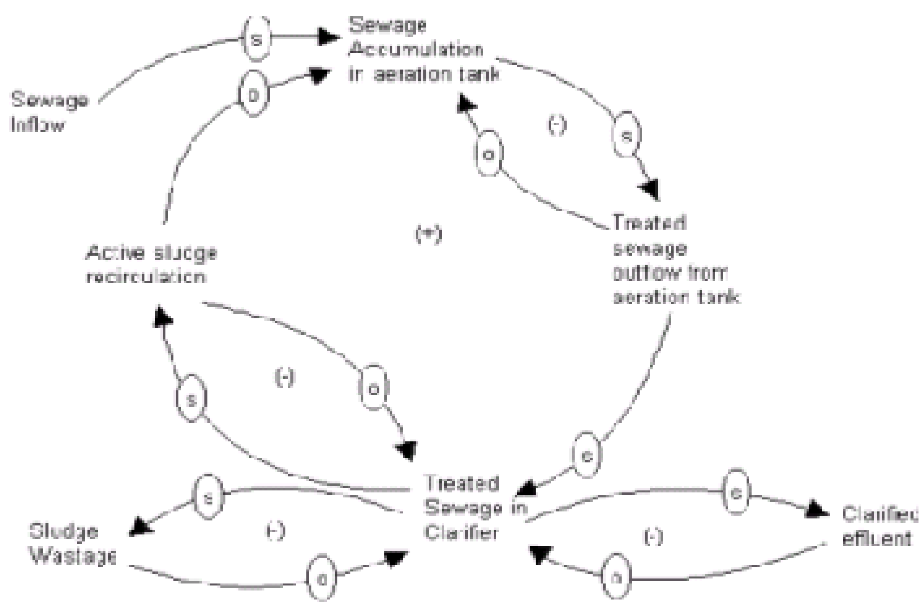


Figure 2 Causal Loop Diagram for Sewage Quantity

Figure 3 is the causal loop diagram for the flow of Biomass. With the inflow of wastewater, the biomass inflow increases, resulting in a rise in total biomass in the aeration tank. This rise in the level of biomass raises the biomass generation rate within the tank, resulting in a positive feedback loop. The increase of biomass leaving rate through the outflow from the tank causes an increase of biomass in the clarifier and an increase of biomass leaving rate through the clarified effluent. The increase of biomass trapped in the clarifier increases the formation of sludge and increases both the biomass re-circulated as active sludge and the biomass leaving the system through the waste sludge. However, both the outflows reduce the biomass trapped in the clarifier.

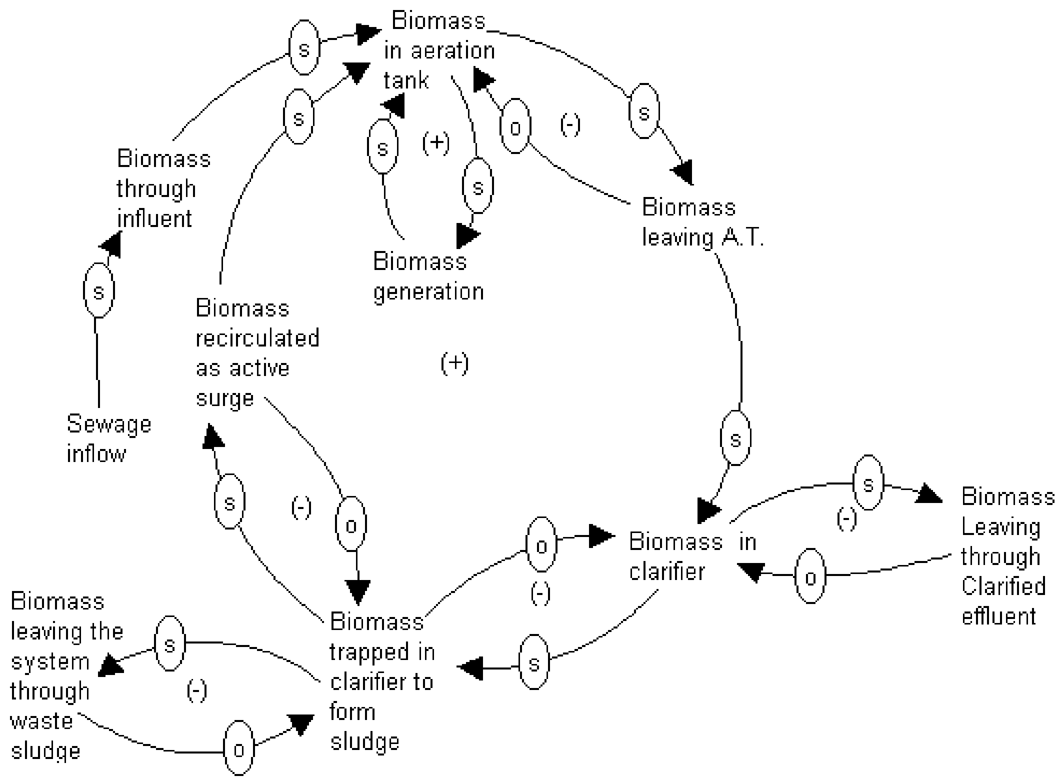


Figure 3 Causal Loop Diagram of Biomass in Activated Sludge Treatment System

Flow of Substrate

Figure 4 is the causal-loop diagram for the flow of substrate. It shows that as the inflow of sewage increases, the substrate coming with the influent increases and so does the substrate accumulation in the aeration tank that enhances the specific biomass growth rate and substrate outflow through the effluent. A rise in the specific biomass growth rate raises the specific substrate consumption rate and lowers the substrate accumulation level in the aeration tank.

Flow of Dissolved Oxygen

Figure 5 is the causal-loop diagram for the dissolved oxygen (DO) in the activated sludge treatment system. The atmospheric oxygen gets transferred to the wastewater environment with the help of surface aerators. Therefore any rise in oxygen transfer rate raises the DO concentration in the aeration tank. This outflow from the aeration tank depletes the DO level in the aeration tank, thereby reducing the DO concentration at the aeration tank.

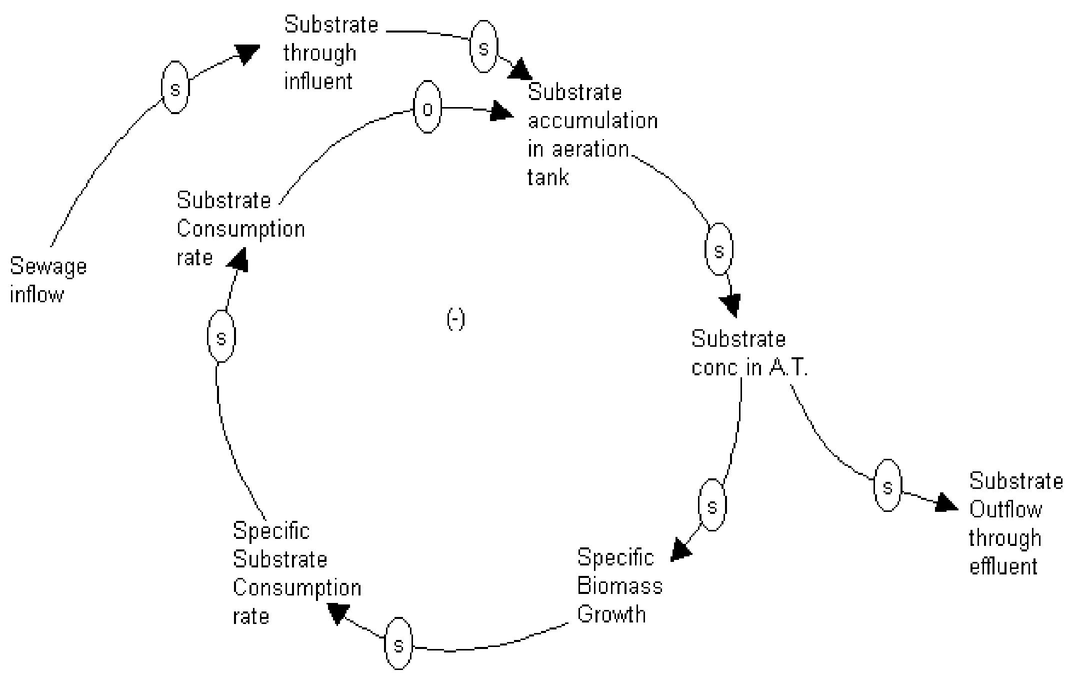


Figure 4 Causal Loop Diagram of Substrate in Activated Sludge Treatment System

The reduction in DO concentration at the aeration tank increases the gap between the oxygen level in the water environment and that in the air environment. This increases the oxygen assimilation rate and the oxygen transfer rate. The DO level in the aeration tank decreases as the biomass utilizes it for respiration.

The well-known equation of Monod (Monod 1949) has been used here to model biomass growth rate and past works by Arceivala (1981), Grady And Lim (1980), and by Sincero and Sincero (1996) are used to model the dissolved oxygen transferring ability of the aerators, oxygen assimilation capacity of waste water, and the dissolved oxygen utilization rate by the biomass.

The Base Run

The following considerations are made for the base model run.

1. The biomass culture is a unique mixture, viable and typically acclimatized with domestic sewage in aerobic environment.
2. The pollution (substrate) is of soluble and readily biodegradable carbonaceous nature, and is measured in terms of Chemical Oxygen Demand (COD) expressed as kg of COD/m^3.
3. The extended aeration version of activated sludge treatment system is considered for modeling, with an average hydraulic retention time of 16 hours.

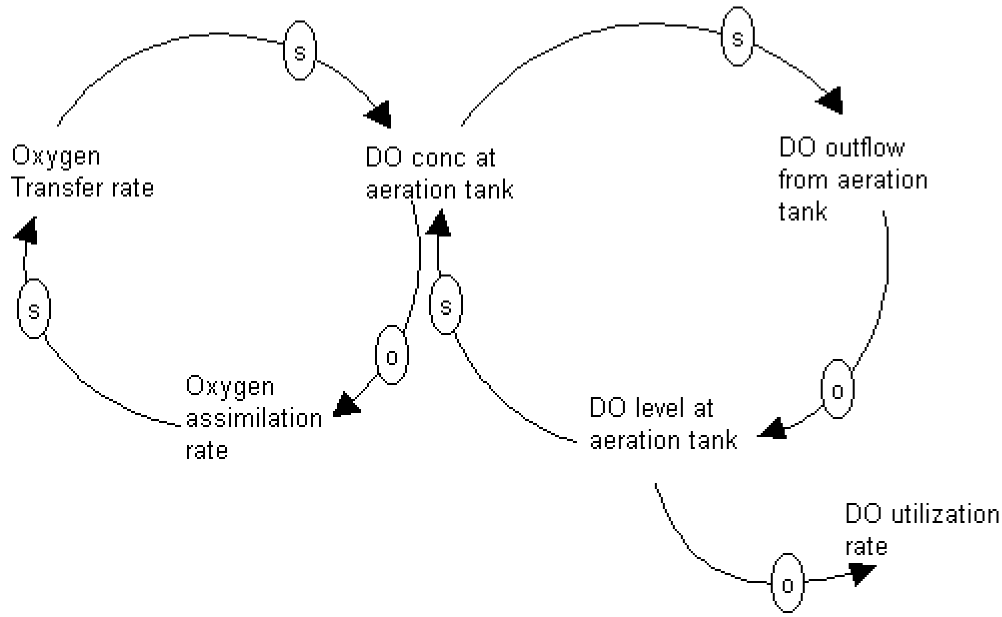
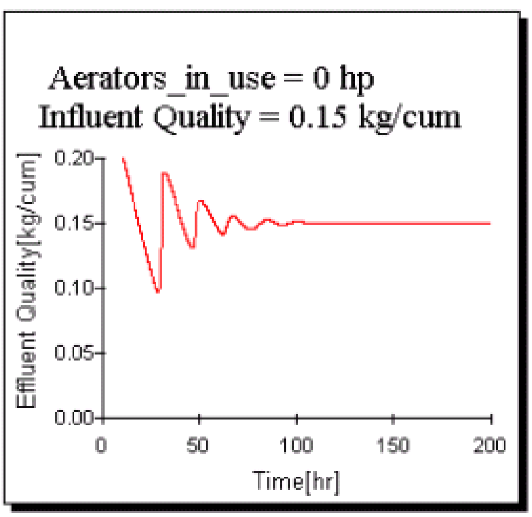


Figure 5: Causal loop diagram of Dissolved Oxygen in Activated Sludge Treatment System

4. The volume of sewage in aeration tank is 3200 m^3 and is full with sewage at the start.
5. Initial average inflow rate of sewage is 200 m^3/hr.
6. The initial influent biomass concentration is 0.002 kg of COD/m^3 and the initial influent substrate concentration is 0.15kg of COD/m^3.
7. Following Mynhier and Grady (1975), the typical saturation substrate constant and the typical maximum specific biomass growth rate are taken as 0.06 kg of COD/m^3 and 0.13 kg/kg/hr respectively; the typical biomass decay coefficient is taken as 0.003 per hour; and the typical biomass decay coefficient is taken as 0.003 per hour.
8. The dissolved oxygen and other nutrients such as Nitrogen and Phosphorous are assumed to be maintained continuously at a level adequate for proper biomass growth.
9. The sludge recirculation ratio is kept constant at 0.8.

The Powersim software package was used to simulate the model. The model was run for 200 hours. Extensive validation testing was done and the results obtained were plausible. Following initial results that appeared to be favourable, the sludge recirculation ratio was taken constant at 0.65. For the purpose of model validation, a modular rise in the value of aerators-in-use was considered: 0, 50 hp, 100 hp, and 150 hp.

Figure 6 shows the graphical response and a portion of simulated values in a tabular format when 'Aerators_in_use' is zero and a uniform average inflow with influent substrate concentration of 0.15 kg/ m^3 keeps on coming during the test period. The result shows that after an initial transience the effluent quality equals the influent quality. In the absence of aerators oxygen is in short supply and this causes drastic reduction in biomass growth and hence the effluent quality does not improve in this case.



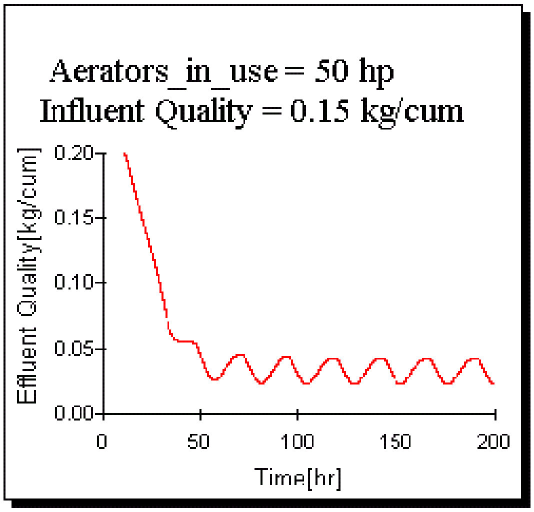
Aerators_in_use = 0 hp
Influent Quality = 0.15 kg/cum

Time	Effluent_Quality
100	0.152
101	0.152
102	0.152
103	0.152
104	0.151
105	0.151
106	0.151
107	0.151
108	0.15
109	0.15
110	0.15

Figure 6 Effluent Quality response for Aerators_in_use = 0hp

Figure 7 shows the graphical response and a portion of simulated values in a tabular format for the run results considering the capacity of 'Aerators_in_use' as 50 hp. The system stabilizes after almost fifty hours and the effluent quality improves as expected and achieves an average value of 0.032 kg/m^3, about five-time improvement over the influent quality.

Table 1 shows the average final values of effluent quality for different values of aerators in use. We see that in general when aerators_in_use increases, the effluent quality improves. However, for 150 hp aerators in use, the effluent quality deteriorates. A reason for this to happen is that higher availability of oxygen raises the biomass level to such a high level that food is not sufficient to sustain their growth. This results in a fall in the biomass level and deteriorates the effluent quality.



Aerators_in_use = 50 hp
Influent Quality = 0.15 kg/cum

Time	Effluent_Quality
100	0.032
101	0.0292
102	0.0265
103	0.0245
104	0.0235
105	0.0234
106	0.024
107	0.0255
108	0.0276
109	0.03
110	0.0325

Figure 7 Effluent Quality response for Aerators_in_use = 50 hp

Table 1: Final Effluent Quality for Different Aerators_in_Use

Aerators_in_use (hp)	Avg Final Effluent Quality (kg/m^3)
0	0.15
50	0.032
100	0.029
150	0.0298

The test results indicate also that for the given set of influent conditions, the maximum total capacity of aerators should be limited to 100 hp in order to achieve a satisfactory effluent quality.

Analysis of Simulation Experimental Results: The 3^2 Design

In order to find out the extent of influence the aerators in use and the recirculation ratio have on the effluent quality, we now simultaneously change the values of the aerators in use and the recirculation ratio. For the purpose of analysis of simulation results, we consider these two factors, and consider three levels for each of these factors:

Factors	Levels
Aeration-in-use	50 hp, 100 hp, 150 hp
Sludge Recirculation Ratio	0.1, 0.5, 0.8

For each combination of factors, we replicated the simulation experiment four times with different noise levels. To induce the desired noises, (1) normal random noises were introduced in four variables: (a) Influent substrate concentration, (b) Influent dissolved oxygen concentration, (c) Influent biomass concentration, and (d) Net biomass production rate, and (2) different seeds were used in the random number generators.

Noises were assumed to follow normal distribution with zero mean. The standard deviations were chosen in a manner such that the steady state values of the uncontaminated variables were at least 4 times the standard deviations of the noises, so as not to result in any unrealistic negative values of the variables in the presence of the noise.

The model was simulated under the conditions stated above. Analysis of variance was done on the simulation results. Table 2 gives the ANOVA table. It is seen that the effect of aeration-in-use, sludge recirculation ratio, and their interaction effect are significant in explaining the variation in the average effluent quality. From the F-values it is inferred that the recirculation ratio has the highest leverage in explaining the variations in effluent quality, followed by the aerators in use and their interaction.

Table 2: ANOVA Table for 3^2 Design

Source of Variation	Sum of Squares SS	df	Mean Sq. MS = $\frac{SS}{df}$	$F_0 = \frac{MS}{MS_{error}}$	Remarks
Sl. Recirculation Ratio	0.0030265	2	0.0015132	408564	
Aerators-in Use	0.0004521	2	0.000226	61020	σ_{error} =
Interaction	0.0007343	4	0.0001835	49545	0.0000608
Error	0.0000001	27	3.7037×10^{-9}		
Total	0.0042131	35			

$F_{0.05, 4, 27} = 2.73$; $F_{0.05, 2, 27} = 3.35$

CONTROL STATEGIES

The operational strategies are to be developed for (1) controlling the exceedence of the effluent quality from the permissible output quality and (2) minimizing the aerator energy consumption. Following the commonly recommended control strategies in modern control theory two broad categories of strategy are adopted here: (1) Open-loop control and (2) Closed-loop control.

Open-loop Control

In the open-loop control strategy, the feedback information on the effluent quality is not used to design the control variables. We have used the following two types of open-loop control strategies: (1) Constant control and (2) Time-varying control.

Constant Control

Here the two control variables (aerators-in-use and sludge recirculation ratio) were held constant during the entire simulation run of the model. The following values were assumed for the two control variables:

Aerators-in-Use : 50 hp, 75 hp, and 100 hp.
Sludge Recirculation Ratio : 0.1, 0.5, 0.65, and 0.8.

Following the temperature variations normally experienced in the eastern coastal India, the model assumed the temperature to vary from a minimum of 8^0C at 12 midnight to a maximum of 16^0C at noon during winter and from a minimum of 18^0C at midnight to a maximum of 24^0C at noon during summer. Mimicking the normal pattern of diurnal variations of inflow rate in municipality water systems, the model assumed the inflow rate to vary during a day, taking a minimum of 75 cubic meters per hour at 00 hour and a maximum of 250 cubic meters per hour at 08 hour. The model was tested with various factor combinations of diurnal variations in temperature and inflow rate.

The simulation results for the effluent quality for the period 100-200 hours (neglecting the initial transient period between 0-100 hours) were transferred to an Excel file through the DDE [Dynamic Data Exchange] facility of the Powersim Package to facilitate statistical computation.

The criteria for selecting the best policy are given below in the decreasing order of priority:

- Meeting the effluent quality norm, i.e., minimizing the deviation of the mean steady-state effluent quality from its target value.
- Minimizing the standard deviation of the effluent quality.
- Minimizing the energy expended in the aerators.

Figure 8 shows, for summer, the variations in the mean effluent quality with the variation in recirculation ratio for different values of aerators-in-use. Figure 9 shows similar results for winter. As sludge recirculation rate rises, bacteria level rises in the aeration tank. It degrades the sludge and improves the quality. Beyond a recirculation ratio value of 0.65, however, the biomass population becomes excessive, going beyond the biomass growth sustainable by the amount food in the wastewater, and thus deteriorates the effluent quality.

To find out the best policy for each season, statistical tests of hypothesis are carried out (reported elsewhere, Das 2003). The tests indicate that the strategy of using a sludge recirculation ratio of 0.65 and aerators-in-use of 100 hp gives the best effluent quality for each season.

Time-Varying Control

Table 3 gives the configuration of aerator-in-use under time-varying control strategy. Taking a cue from the constant-control results, the sludge recirculation ratio was kept at a constant value of 0.65. The capacities of aerators to be deployed at various times of the day are selected to take care of the diurnal variations of temperature and inflow rate. Thus, the highest capacity of aerators is deployed during the 08-20 hours and the lowest capacity was deployed during 00-04 hours.

Considering that testing of effluent quality for COD values involves digestion, cooling and titration and requires about 4 hours, the inflow rate variations were considered in a time slot of 4 hours in a day. The configuration of aerators in use for the time-varying control strategy followed for the model simulation is shown in Table 3.

The model results for the effluent quality are taken to an Excel file and the corresponding statistical values, mean and standard deviation are calculated. The total aerator energy (hp-hr) consumed during the period 100-200 hour is given in Table 4. A study of the results reported in

Table 4 indicates that all policies 1, 3, and 5 for winter give acceptable effluent quality values, but the aerator energy is the minimum for policy 1. Thus policy 1 is considered the best for winter. For summer, however, only policy 6 (out of the policies 2, 4, and 6) gives effluent quality values within acceptable range. Thus policy 6 is considered the best policy for summer, although it requires the maximum aerator energy.

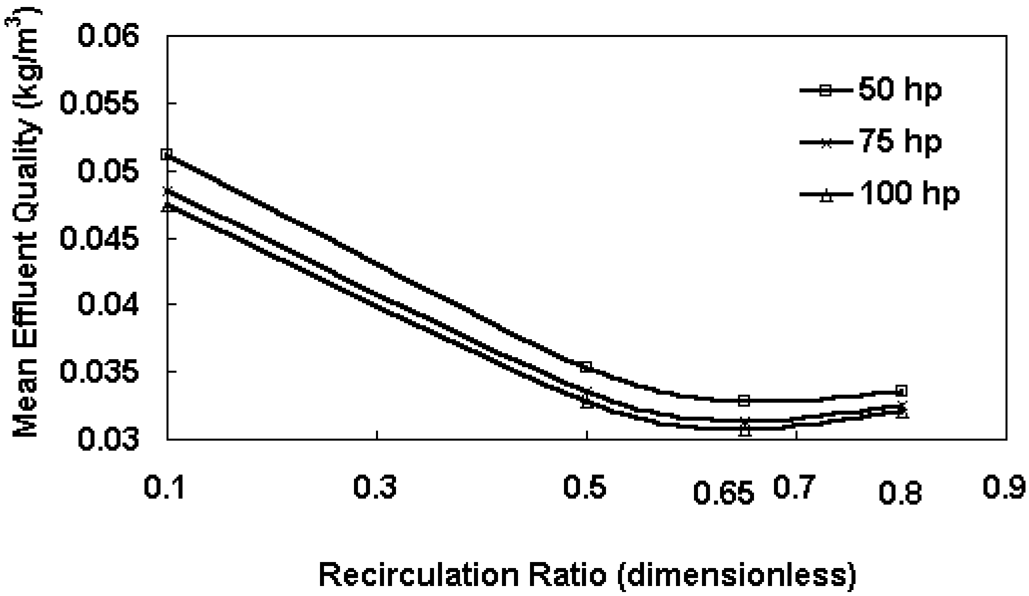


Figure 8 Mean Effluent Quality in Summer

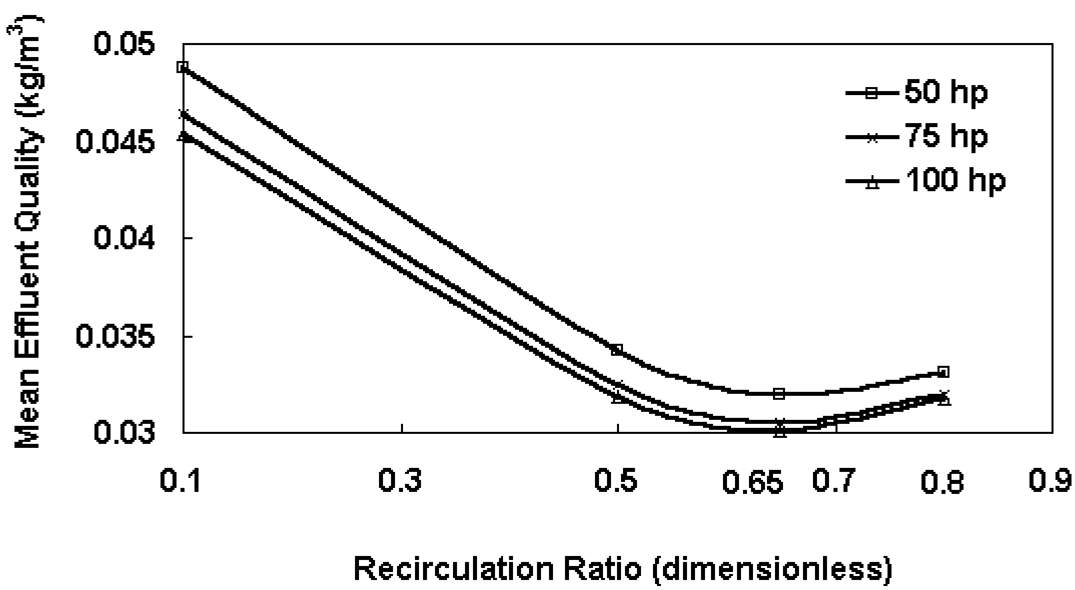


Figure 9 Mean Effluent Quality in Summer

Table 3: The Configuration of Aerator-in-use under Time-Varying Control Strategy

Policy No.	Sludge Recirculation Ratio	Season	Aerator-in-Use (hp)			
			0-4 hrs	4-8 hrs	8-20 hrs	20-24 hrs
1	0.65	Winter	25	50	75	50
2		Summer	25	50	100	50
3	0.65	Winter	25	50	100	50
4		Summer	25	50	100	50
5	0.65	Winter	25	75	100	75
6		Summer	25	75	100	75

Closed Loop Control

Under this control strategy, a feedback information flow from the response variable is used to decide the control variable value. Two categories of feedback control strategy are used in this investigation: (1) Output feedback control and (2) Output integrated feedback control [Cusum control].

Table 4: Effluent Quality under Time-Varying Control Strategy

Policy No.	Sludge Recirculation Ratio	Season	Aerator-in-use (hp)				Effluent Quality (kg/m^3)		Aerator Energy (hp-hr) [10- 200hr]
			0-4 hrs	4-8 hrs	8-20 hrs	20-24 hrs	Mean	Standard Deviation	
1	0.65	Winter	25	50	75	50	**0.03083**	**0.00499**	**5800**
2		Summer	25	50	100	50	0.0316	0.00513	5800
3	0.65	Winter	25	50	100	50	0.03045	0.00469	7000
4		Summer	25	50	100	50	0.03123	0.00481	7000
5	0.65	Winter	25	75	100	75	0.03021	0.00476	7900
6		Summer	25	75	100	75	**0.03095**	**0.00489**	**7900**

The strategy of basing the sludge recirculation policy on the information on food-to-microorganism ratio belongs to the category of *state feedback control*. This category of control has not been investigated any further here for two reasons. The first reason is that this strategy has been already studied in great detail and presented earlier (Das *et al*. 1995). The second reason is that the time to measure the biomass concentration and the substrate concentration in the aeration tank usually takes 12 hours (considering time for muffle furnace heating and cooling) and 4 hours respectively, making regular monitoring of these variables an impractical proposition.

Output Feedback Control

Here the information on effluent quality is fed back to compare with the desired effluent quality. The deviation from the desired value actuates the policy of aerators to be deployed. The strategy allows an increase in aerators-in-use whenever effluent quality deteriorates and a decrease in aerators-in-use whenever the quality improves. The increase in aerators-in-use is carried out in a modular fashion, in steps of 25 hp each, with the aerator capacity ranging between 25-100 hp.

We assumed that the effluents are sampled every fourth hour to measure its quality and actuate the control. The threshold values of effluent quality are fixed considering that its mean and standard deviation values are around 0.03 kg/m^3 and 0.005 kg/m^3 respectively.

Table 5: Output Feedback Control Strategy

Effluent Quality (kg/m^3)	Aerators-in-use (hp)
effluent quality $\leq$ 0.025	25
0.025 $<$ effluent quality $\leq$ 0.03	50
0.03 $<$ effluent quality $\leq$ 0.035	75
effluent quality $>$ 0.035	100

Taking cue from the results of open-loop control, the recirculation ratio was fixed at 0.65 in both winter and summer. As before, the mean and standard deviation of effluent quality and the aerator energy expended are used as the criteria to compare performance of control strategies.

The ‘slider-bar’ facility in the Powersim package has been used for changing the value of aerators-in-use within the simulation run. Depending upon the effluent quality value for each sample period of four hours, the value of aerator-in-use has been changed as per Table 5. The mean and standard deviation of the effluent quality have been computed through an Excel file.

The corresponding aerator-energy consumption values were computed and are given along with other results in Table 6. When compared with the best open-loop control policy (i.e., the time-varying control), the closed-loop control policy performs better with regard to energy spent in aerator with comparable values of mean and standard deviation of the effluent quality for the summer season. In winter, however, the time-varying control gives better effluent quality characteristics with less aerator energy compared to the feedback control.

Table 6: Effluent Quality under the Feedback Control Strategy

Sl No.	Season	Effluent Quality (kg/m^3)		Aerator-Energy (hp-hr)
		Mean	Standard Deviation	
1.	Summer	**0.03051**	**0.0052**	**7300**
2.	Winter	0.03051	0.0052	6995

Output-Integrated Feedback Control (Cusum Control)

Integral control works on the basis of integrating or accumulating the deviations of the response variable from its target value and using this information to design the control variable. In the field of statistical control this idea has been utilized to develop the concept of Cusum (Cumulative sum) chart. Figure 10 gives a schematic diagram of this form of control. The difference from an output feedback control strategy is that the error signal is integrated here before actuating the control.

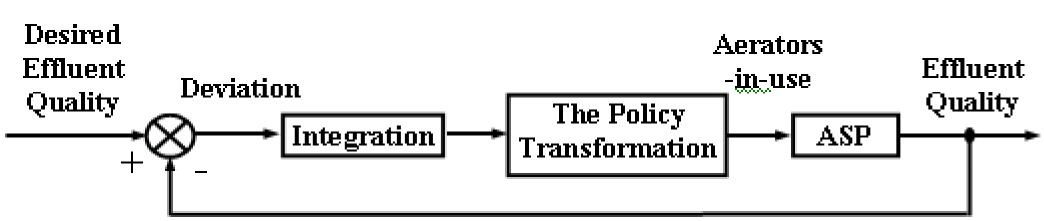


Figure 10 Output-Integrated Feedback Control

In the present investigation an attempt is made to use cusum control as a strategy for getting acceptable effluent quality. The standard procedure for cusum control [Mitra, 1998] requires (1) the knowledge of the target value of the effluent quality $\overline{X}$, the standard deviation (σ_x) of effluent quality, and (2) a specification of the extent of its deviation from the target. For the purpose of this study the following values are adopted: $\overline{X}$ = 0.03 kg/ m^3, σ_x = 0.005 kg/ m^3, and $\Delta\overline{X}$ = 0.00125 kg/ m^3.

The cusum control is normally implemented with the help of a V mask whose parameters (the lead distance, d, and the angle of decision line θ) are computed from the knowledge of the above-mentioned values for an acceptable level of significance. For a level of significance of 0.05, the lead distance, d, equals 23.96, and the angle of decision line, θ, is 7.12^0.

The usual procedure to implement cusum control is to sample output values at regular intervals, take their average, compute their deviations from the target value, accumulate the deviations as time progresses, and plot them. The V-mask is then positioned on the chart such that its axis is parallel to the horizontal axis and the midpoint of the vertical line of the V-mask coincides with the last plotted cumulative sum of the deviations. If any past plotted value goes beyond either of the two arms (decision lines) of the V-mask, the process is considered out of control.

The above-mentioned procedure is adopted in the present study in the following manner:

1. Effluent quality is sampled four times at an interval of 0.25 hour during the last hour of every four-hour interval, after the steady state condition was obtained (i.e., after 100^{th} hour).
2. These effluent quality values were numerically averaged.
3. The model was simulated with pause at every fourth hour. The numerically averaged effluent quality was tabulated.
4. The deviations of the average effluent quality from its target value were computed. The accumulated deviations were also computed and plotted on a graph paper.
5. A V-mask, previously prepared on a paper with the computed values of parameters d and θ, was placed on the plot of the accumulated effluent quality as mentioned earlier.
6. Whenever any past plotted value of accumulated effluent quality went outside the two arms of the V-mask, the process was considered out of control.
7. Following the usual practice in statistical process control, whenever a control action is taken following an out-of-control point, the error corresponding to that point is set at zero for accumulation at all later time points.

8. The slide-bar facility of the Powersim package was used to change the value of aerators-in-use during the simulation of the model.
9. The effluent quality values were transferred to an Excel file for computation of its mean and standard deviation.

The strategy for Cusum Control is shown in the Table 7.

Discussion on the results of Cusum Control Chart:

The mean average effluent quality came out to be 0.0031057 kg/m^3 with the standard deviation of 0.00592 kg/m^3. The aerator energy consumption doing 100th to 200th hour also came out to be 8600 hp-hr. Neither quality-wise nor energy consumption-wise, this control strategy gave a superior result compared to those for the time-varying open-loop control strategy. This inferior result can be explained from the fact that the cusum control was applied in a sampled manner after every four hours and during that time the under-controlled sewage passes though the reactor-system. Reducing the sampling interval was however not a practical proposition for the reasons cited earlier.

Table 7: Strategy for Cusum Control

Cusum Chart Results	Action required
Process mean has shifted to a higher value, indicating deterioration of the effluent quality	Increase the aerator-in-use by 1 step (25 hp).
The process mean has shifted to a low value indicating improvement of effluent quality.	Decrease the aerator-in-use by 1 step (25 hp).
The effluent quality is within the accepted range	No change is needed in aerators-in-use.

A Comparison of the Best Control Strategies

Table 8 and Table 9 give the results for the best control strategies obtained so far for winter and summer respectively. The winter results (Table 8) indicate that as far as the aerator energy is considered, time-varying control gives the best result. But the same thing cannot be said about this strategy when effluent quality is considered. Strategies 1, 2 and 3 are the candidates.

Because of the extremely high aerator energy requirement, the strategy of constant control is ignored here. A statistical test of hypothesis is done here to compare the mean effluent quality for the time-varying control strategy with that for the output feedback control. The Z-statistic is evaluated and compared with the $Z_{0.005}$ value obtained from the standard normal table. The hypotheses selected are: H_0: $\mu_2 = \mu_3$, H_1: $\mu_2 > \mu_3$. The test statistic values were obtained as: $Z_0 = 2162.88$ and $Z_{0.05} = 1.645$. Thus the null hypothesis is rejected at a 5% level of significance and it is inferred that as far as effluent quality is concerned, output feedback control is the best strategy.

Table 9 (for summer) indicates that output feedback control is the best if the aerator energy requirement is considered. It is also the best if only the mean effluent quality is considered. But when one considers the standard deviation of the effluent quality the time-varying control strategy appears to be a candidate. The test of hypothesis is carried out to get a clear picture: H_0: $\mu_2 = \mu_3$, H_1: $\mu_2 > \mu_3$, $Z_0 = 123.34$ and $Z_{0.05} = 1.645$. Thus the null hypothesis is rejected. It is inferred that the output feedback control gives the best result considering not only the aerator energy expended but also the effluent quality.

Table 8: Strategy-wise Comparison of the Results (Winter)

Control strategy	Mean	Standard Deviation	Aerator Energy in use
1. Constant Control (RR = 0.65 and Aerator-in-use = 100 hp)	0.03009	0.00507	10000
2. Time Varying Control	**0.03083**	**0.00499**	**5800**
3. Output feedback control	**0.03051**	**0.0052**	**6995**
4. Cusum Control	0.031057	0.00592	8600

In conclusion, it can be stated that output feedback control is the most potent strategy for activated sludge treatment systems during both winter and summer.

Table 9: Strategy-wise Comparison of the Results (Summer)

Control strategy	Mean	Standard Deviation	Aerator Energy in use hp-hr.
1. Constant Control	0.03074	0.00522	10000
2. Time-varying Control	0.03095	0.00489	7900
3. Output feedback control	**0.03051**	**0.0052**	**7300**
4. Cusum Control	0.031125	0.00573	8450

Sensitivity Analysis for the Best Strategy

Although sensitivity tests can be carried out very extensively for changes in the values of many model variables, in what is given below only the variable sensitivity results are cited. The variables selected are the two major variables associated with the inflows: (1) Average Inflow Rate and (2) Inflow Substrate Concentration. Values of these variables are changed one by one and the best policy is run. Table 10 gives the best policy results for the following:

1. The original inflow conditions (i.e., average inflow rate = 200 m^3/hr, and inflow concentration = 0.15 kg/m^3) are maintained.
2. Average inflow rate is reduced to 150 m^3/hr, with other variables remaining at their base values.
3. Inflow substrate concentration is increased to 0.20 kg/m^3, with other variables remaining at their base values.

Reduction of inflow rate by 25% improves the value of mean effluent quality by about 10% with reduction in its standard deviation. Simultaneously, aerator energy expended reduces by nearly 50%. Such an improvement is expected and improves the credibility of the policy.

In the second policy sensitivity test, however, when the inflow substrate concentration is raised by 33%, the mean effluent quality deteriorates by about 23%, with a fall in aerator energy expense by about 12%. In spite of the use of the feedback control strategy, the effluent quality has deteriorated due to a limitation on imposed maximum aerator capacity of 100 hp.

It only means that the initial design of limiting the aerator capacity was not correct. It is expected that if the maximum aerator capacity value were increased, and the feedback control strategy was designed accordingly, the results would be very acceptable. The maximum aerator capacity is increased to 125 hp and thereafter to 150 hp. It is observed that when the model is run with the same control strategy and with 150 hp as max aerator-in-use, the effluent quality improves (with a reduction of its mean value to 0.030532 and a standard deviation of 0.00616) but the total aerator energy increases to 12900 hp-hr.

It is therefore concluded that the output feedback control strategy holds good for higher influent substrate concentration value with high.

Table 10: Sensitivity Analysis for the Best Strategy

	Effluent Quality (kg/m^3)		Aeration Energy (hp-hr) (Between 100-200 hr)
	Mean	Standard Deviation	
Best Policy Average Inflow Rate = 200 m^3/hr Inflow Sub Case = 0.15 m^3/hr	0.03051	0.0052	9800
Average Inflow Rate = 150 m^3/hr Other parameters at base values	0.027164	0.0044763	5000
Inflow Substrate Concentration = 0.20 kg/m^3 Other parameters at base values	0.037533	0.0065711	8600

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