Operating space diagrams: a tool for designers of wastewater treatment plants

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Abstract Recent years have seen the introduction of new and varied designs of activated sludge plants. With increasing needs for higher efficiencies and lower costs, the possibility of a plant that operates more effectively has created the need for tools that can be used to evaluate and compare designs at the design stage. One such tool is the operating space diagram. It is the aim of this paper to present this tool and demonstrate its application and relevance to design using a simple case study. In the case study, use of the operating space diagram suggested changes in design that would improve the flexibility of the process. It also was useful for designing suitable control strategies.

Keywords Activated sludge process; design; operating space diagrams; resilience; flexibility; simulation studies

Introduction

We are witnessing a dramatic growth world-wide in biological nutrient removal technology for wastewater treatment. As a consequence, there is growing debate about the best designs and mode of operation. Design of BNR (biological nutrient removal) plants, particularly those operated in the continuous mode, has received considerable attention. Until now the focus of the design methods has been to minimise capital costs. Another factor, which is just as important, is the operability of the plant. This is usually not considered at the design stage. Consequently, wastewater treatment plants have often proved difficult to operate.

The concept of integrating operability in the design of processes is not new (Grossmann and Morari, 1983; Stephanopolous, 1983; Perkins, 1992). A standard design procedure demonstrating at what point this would be applied is given in Figure 1. The figure indicates that in the design of wastewater treatment plants, a number of the key stages are not included. The choice between alternative designs is typically made on the designers' preference. Modelling of the alternative designs is not usually performed. Whilst cost analyses are usually performed, there is no analysis of controllability and operability.

The operability of a process refers to its ability to perform satisfactorily under conditions different from the nominal design conditions (Grossmann and Morari, 1983). It incorporates the six components given in Figure 2. The most operable process is highly flexible, highly resilient, safe and reliable, controllable, simple to operate and easy to start-up and shut-down.

There has been considerable effort devoted to the development of tools to assess whether or not a process is controllable and there are now qualitative and structural controllability tools available. Given that it is already known that ASPs (activated sludge processes) are controllable (Steffens, 1997), and that reviews of such tools already exist, it is unnecessary to study them here. Instead the key aspects to address are, how easy are the processes to control, that is, how resilient are they, and how easily do they cope with long term changes, that is, how flexible are they. A tool that can be used to investigate these aspects is the operating space diagram.

Operating space diagrams are steady state contour plots of the outputs of a process at different values of the manipulated variables. They are useful as visual tools of the behaviour

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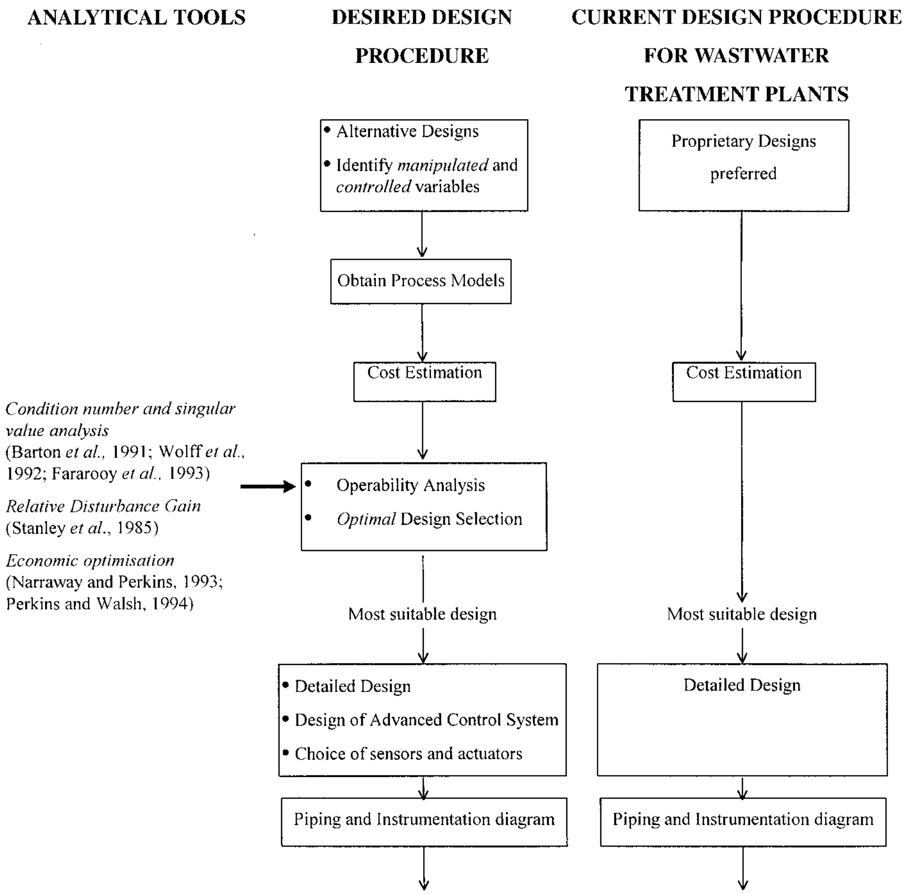


Figure 1 Methodology for integrating process design and control showing the difference between the desired methodology and that generally used by wastewater design engineers

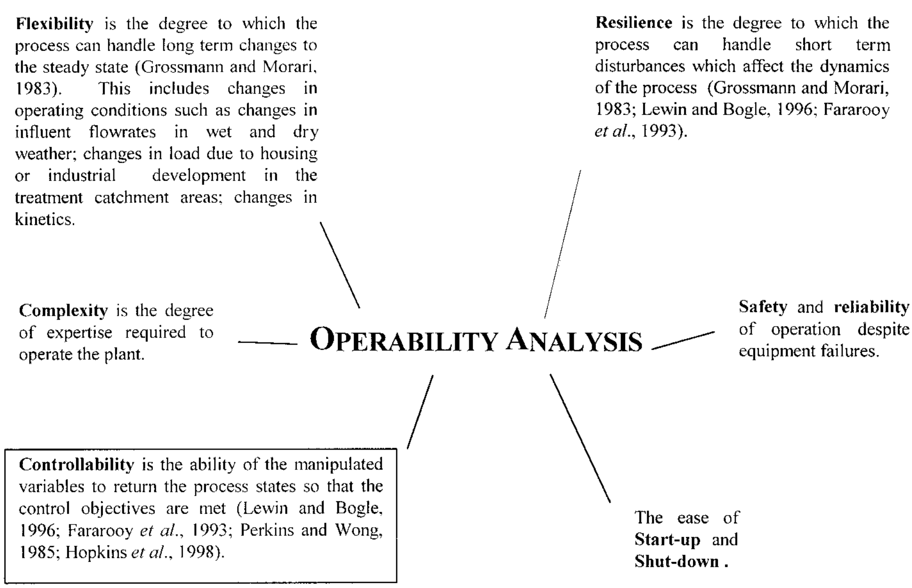


Figure 2 The components of operability

of processes. They provide:

- understanding of the behaviour of the processes over a range of operating conditions;
- information about the position of the optima and their relationship to the constraints;
- information about the position of constraints, which are the active constraints, and why;
- the sensitivities of the outputs of the processes to the manipulated variables and what appropriate control strategies could be implemented.

This information provides insight into the flexibility, the capital costs and the resilience of the processes respectively, making them useful tools in process design. This will be demonstrated in the following section using a case study. A plant will be designed and then analysed using the procedure outlined in Figure 1. The analysis of operability will be performed by studying some operating space diagrams for the given design.

The case study

A plant was designed based on the characteristics of a full scale operating plant (8 Ml/day) located north of Brisbane, Australia (Table 1). The plant is a biological carbon and nitrogen removal plant. A modified Ludzack-Ettinger process (Figure 3) was designed using the design method reported in WRC (1984). This design method requires the following:

- the choice of a suitable sludge age, R_S; a sludge age of 10 to 20 days is considered sufficient to allow nitrifiers to grow;
- the choice of a safety factor, s_f, on nitrification capacity to ensure the aerobic basin is large enough to allow for sufficient nitrification;
- a hydraulic residence time chosen to allow the MLSS concentration required for adequate removal, determines the process volume, V_P;
- the choice of the operational variables, sludge recycle and internal recycle, to maintain contact of biomass with influent and nitrate with denitrifiers respectively; and
- the size settler area, A_S, is chosen to ensure separation and the total volume, V_S to provide storage capacity of the solids.

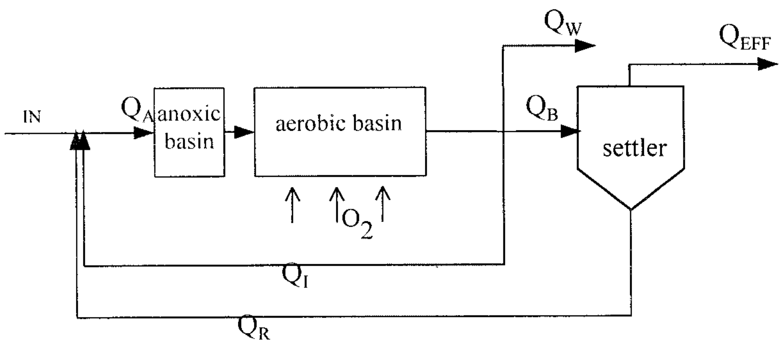


Figure 3 The modified Ludzack-Ettinger process

Table 1 The characteristics of a full-scale plant

Wastewater Characteristic	Influent value	Effluent requirements	Units
Influent flowrate	8		Ml/day
TCOD	700	<35	mg/l
Fraction RBCOD	0.46		
Unbiodegradable soluble COD fraction	0.13		
Unbiodegradable particulate COD fraction	0.02		
TKN	40	<5	mg/l
Unbiodegradable soluble N	6		mg/l
Ammonia	30	<1	mg/l

The design parameters used are given in Table 2. Stoichiometric and yield coefficients required for the design were taken from Henze *et al*. (1987) and WRC (1984).

The resulting design is given in Table 3. A sensitivity analysis was performed on the design to determine the effects of the design parameters. This involved changing the design parameters one at a time and then redesigning the process. The resulting designs for the more significant parameters are given in Table 3.

The variable that has most affect on the process volume is the sludge age, R_S. The smaller the sludge age, the smaller the process and consequently, the lower the nitrification capacity. The cost of a plant with a sludge age of 25 days is almost double that of a plant with a sludge age of 10 days. A sludge age of 25 days would guarantee nitrogen removal but would be expensive, a sludge age of 10 days may not guarantee nitrogen removal but would be half the price.

Rather than increase the volume of the process in order to guarantee nutrient removal, it would be more cost effective to redistribute the volumes of the units within the process. The parameters that affect the distribution of the unit volumes are the MLSS concentration, X_t, and the safety factor, s_f. It is possible that appropriate choices of these variables will result in better nutrient removal at no extra cost.

The methodology described in Figure 1 was followed to analyse the process. The results are described next.

Identify manipulated and controlled variables

There are four manipulated variables; the wastage, Q_W, the sludge recycle, Q_R, the nitrate recycle, Q_I and the dissolved oxygen concentration in the aerobic basin. The flowrates are constrained by maximum pipe sizes and the oxygen concentration by maximum compressor capacity.

The controlled variables include the solids concentration in the effluent of the settler and the total nitrogen concentration in the effluent. Minimal values for each were defined and incorporated as constraints on the model of the process. They are given in Equations 1 and 2.

Table 2 Design parameters for the continuous activated sludge process (values from WRC, 1984)

Design parameters	Value	Unit
Design R_S, sludge age	18	days
s_f, safety factor with respect to nitrification	2.5	
Sludge recycle rate (ratio to feed)	1	
Oxygen in internal recycle	1.5	mg/l
Oxygen in sludge recycle	0	mg/l
Internal recycle rate (ratio to feed)	9	
Safety factor with respect to settling	1.25	
Depth required to achieved clarification	1.5	m
Percentage of process solids in settler	20	%

Table 3 The continuous plant design

Changes to design	V_p, aeration basin volume (m^3)	f_x, unaerated fraction (%)	MLSS (mg/l)	V_S, settler volume (m^3)	A_s, settler area (m^2)
Base Case	5240	22	5000	1825	675
R_S = 10	3220	6.3	4500	1250	500
= 15	4075	17	5000	1825	675
= 25	5820	25	5500	2430	900
X_t = 4000	6550	22	4000	1500	375
= 6000	4370	22	6000	2640	1200
s_f = 1.5	5240	53	5000	1825	675

Effluent total nitrogen ≤ 5 mg/l (1)
Effluent suspended solids ≤ 0.05 g/l (2)

Model the process

The reactions were modelled using the IAWQ Model No. 1 (Henze *et al*., 1987) and the settling by a layer model (Takacs *et al*., 1991). A model of the process was constructed and simulated in MATLAB™, chosen for its flexibility and in-built mathematical functions.

Cost estimation

A detailed cost estimation is not necessary for the purposes of this study. However, in terms of the conclusions that will be drawn later in the paper, it was assumed that the total cost of the plant is proporional to the total process volume (V_P+V_S).

Analyse the process using the operating space diagrams

An operating space diagram is a contour plot of an output variable against the manipulated variables. It is constructed by calculating the steady state of the process over a range of values for the manipulated variables. It is useful as a visual tool of the behaviour of the process. The diagrams provide information about the position of the optima and their relation to the nominal design points. They show how close these points are to constraints. They also provide information about the sensitivities of the outputs (removal efficiencies) to the manipulated variables. In the following section, one of these operating spaces will be analysed to demonstrate its value to design.

Results

Operating spaces were constructed to study the effects of the manipulated variables given in the previous section. In this section the analysis of the results is confined to the operating space given by the wastage rate Q_W, and the recycle rate, Q_R.

Figure 4a shows the nitrogen removal efficiency at different recycle and wastage rates. This can be compared with contour plots of solids residence time (Figure 4b), the MLSS concentration (Figure 4c), and the solids in the effluent (Figure 4d). One can determine, for example, that to obtain the operation at point d on Figure 4, the wastage must be at 290 m^3/d, and the recycle at 8000 m^3/d. At this point, the SRT is 18 days. The MLSS in the process is approximately 2500 mg/l and the solids in the effluent 0.02 g/l. This point is in fact the design point for the process. It lies within the feasible region as bounded by the process constraints denoted by A for Equation 2 and B for Equation 1. If wastage is decreased and the recycle increased, the operating point will move in the direction of the optimum (the point of maximum nitrogen removal), which lies on the solids constraint.

The charts will now be used to analyse the flexibility and resilience of the process.

A flexibility analysis

The definition of flexibility was given in Figure 2. A measure of flexibility is the size of the operating space that the process can operate within, without violating its constraints. The bigger this feasible region is, and the closer the normal operating point is to the centre of this region, the more flexible the process is. In this section it will be shown that the operating space diagram gives a qualitative view of the process flexibility.

First we consider the bounds on the feasible region in the direction of different wastage rates, that is in the horizontal direction in Figure 4. The nitrogen removal efficiency increases with a decrease in wastage (Figure 4a). This is to be expected given that a decrease in wastage results in an increase in sludge age (Figure 4b) and, hence, a higher concentration of active biomass (Figure 4c). If the sludge age is too high the solids in the

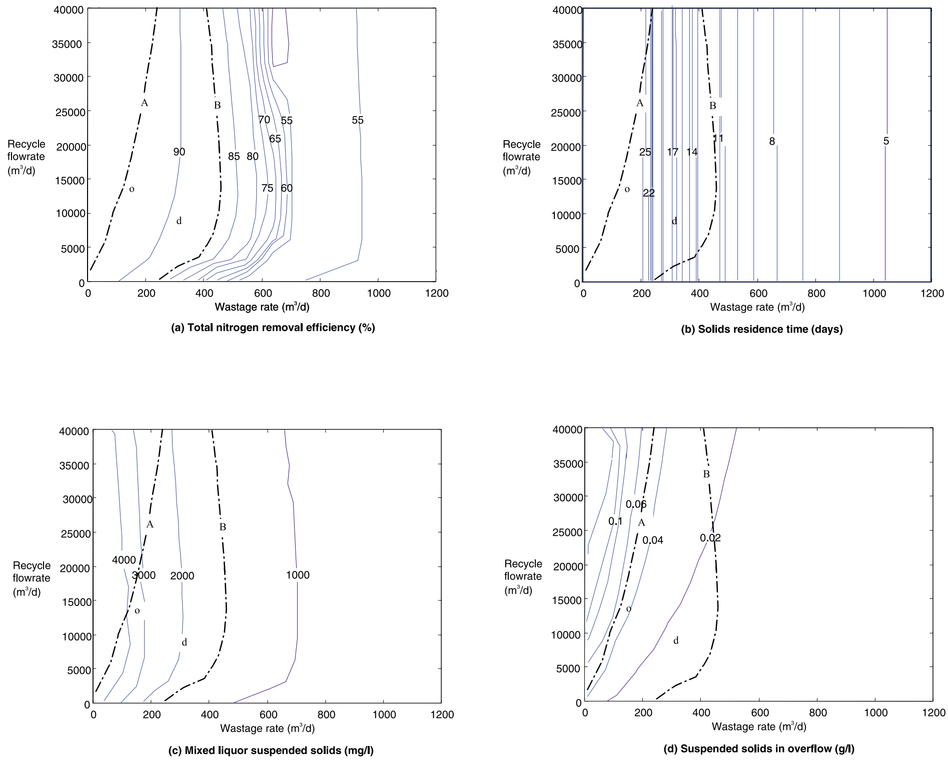


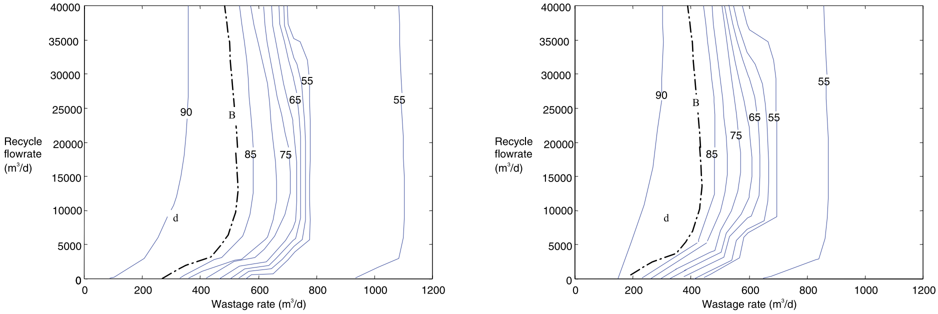
Figure 4 The operating space diagrams for the base case design (A = solids constraint, B = constraint of effluent total nitrogen, o = optimal operation for nitrogen removal, d = design point)

process increase (Figure 4c) and the settler is overloaded as a result (Figure 4d). The solids in the effluent will become too high; that is, they will exceed the constraint on effluent solids concentration (in this case, 0.05 g/l given by A in Figure 4). Conversely, if the sludge age is too low, washout of the autotrophs occurs. The effluent limits are not met because the nitrogen removal efficiency is not high enough. The constraint on nitrogen removal is exceeded (in this case, when the removal efficiency drops below 87% as given by B in Figure 4).

We now consider the bounds on the feasible region in the direction of changing recycle rates. The recycle rate, has no effect on the nitrogen removal efficiency at recycle rates around the design point, although at very low recycle rates it does have some effect. It does affect the solids in the effluent (Figure 4d) because increasing the recycle rate results in increased flow through the settler. That is, the settler becomes overloaded.

In order to increase the flexibility of the process it is necessary to move one of the constraints away from the design point. It is possible to do this by changing the process design. Two of the different designs in Table 3 will now be analysed to demonstrate how this can be done.

Consider the stipulation in the design rules that the design sludge age should be between 10 and 20 days to maintain the autotrophs in the system. What then if the process had been designed for 25 days. Could the size of the operating region, and hence the flexibility, have been increased? This design was given in Table 3 and its operating space in Figure 5a. It is evident that the size of the operating region within the constraints is considerably larger than in the original design because the two constraints have moved away from the design point. The solids constraint, A, moved because the settler was made bigger and the nitrogen removal constraint, B, moved because the hydraulic residence time was increased. Of



(a) Total nitrogen removal efficiency (%) Design R_s=25days

(b) Total nitrogen removal efficiency (%) Design X_t=6000mg/l

Figure 5 The effect of design changes on the operating spaces

course, this increase in flexibility has come at considerable expense. The process is now 17% larger and consequently requires an increase in capital investment.

Alternatively, the process flexibility might increase by increasing the design suspended solids to 6000 mg/l (Table 3). This design has the same total volume as the original design but constraint B has moved slightly closer to the design point of the original design because the hydraulic residence time is smaller and constraint A has moved further away (off the chart) because the settler is bigger (Figure 5b). There is more freedom, that is, flexibility for the operating point to move towards optimal nitrogen removal. Thus, the flexibility of the process has been increased without increasing the total volume of the process.

In summary, the size of the region that the process can operate in, and the position of the nominal operating point within that region, determines the flexibility of the process. In the case study, considerable increases in flexibility were obtained by changes to initial design parameters. In some instances, such changes result in an increase in capital cost, but this is not always the case, as was illustrated in the example.

A resilience analysis

The concept of resilience was defined in Figure 2. It considers the dynamic behaviour of a process. The information about dynamic behaviour that can be gleaned from an operating space comes from the surface profile, that is, the hills and valleys of the operating space and where the design point lies within them. If, for example, the current operation lies on the other side of a hill from the desired operation, then it will be difficult to move the process to that point using a simple controller. In this case, the process is not resilient.

The strategy is to keep the operation within the feasible region and preferably at the optimum. In the previous section we discussed the fact that whilst the wastage rate affected the position of operation with respect to both constraints, the recycle rate has little effect on the total nitrogen removal. Thus, it follows that an appropriate control strategy would be to use the sludge recycle to control the solids in the effluent and the wastage to control nitrogen removal efficiency.

In a resilience analysis we are concerned with the ability of these manipulated variables to move the process to the optimum. In Figure 4a, in the feasible region, the contours in the direction of changing wastage rates are further apart than on the other side of the nitrogen constraint, B. This means that within the feasible region the sensitivity of the nitrogen removal efficiency to changes in wastage is low, and outside, the sensitivity is high. This means that in order to control the process in respect to nitrogen removal efficiency with the wastage rate, a variable gain would be required. A similar conclusion can be drawn with respect to controlling the solids in the effluent using the sludge recycle (Figure 4d).

It is interesting to note that changing the design does not change the variable sensitivity of the outputs to the manipulated variables inside and outside the feasible region (compare Figure 4a with Figures 5a and 5b). However, because the feasible region is now much larger, the process has greater probability of staying within the constraints without requiring the manipulation of the recycle rate.

In summary, it was possible to determine the ability of the manipulated variables to control the outputs using the operating space diagrams. In this instance, changing the design meant that it was no longer necessary to control one of the outputs.

Conclusions

The aim of this paper was to demonstrate the value of performing operability studies during the design of a wastewater treatment process. This step is becoming more important as tightening restrictions on effluent quality demand the need for plants that are easy to operate and control. The tool demonstrated was the operating space diagram. It is a steady state contour plot of the output of a process at different values of the manipulated variables. It provides visual, qualitative information about the behaviour of a process over a range of operating conditions. The paper demonstrated this with a simple case study. An operating space diagram of this case study was analysed to find out about the flexibility and resilience of the process. With this information it was possible to increase the process flexibility with simple design changes, and to determine a suitable control strategy.

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