DETERMINING THE POTENTIAL BENEFITS OF CONTROLLING AN INDUSTRIAL WASTEWATER TREATMENT PLANT

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ABSTRACT

The aim of this paper is to demonstrate a simple methodology for performing a control benefits analysis. This methodology takes a global approach to determining how to improve the process. In the field of wastewater treatment this benchmark study can be a useful tool to investigate whether it is worth upgrading the process. This was proved by applying it to an industrial wastewater treatment plant in Belgium that is currently undergoing a major upgrade in its control system. This was the first application of the method to a full-scale WWTP. The results of the study show the value of performing it at the beginning of an upgrade project. Although the study does not replace the need for a more thorough analysis, it points out the areas that this analysis should focus on. The major conclusion of the paper is that the benefits study not only proves its value at the beginning of a control upgrade, it is also a useful periodical evaluation method that can redirect the project as new data become available.

KEYWORDS

Benchmarking; benefits analysis; process control; self-assessment proforma; wastewater treatment.

INTRODUCTION

At a wastewater treatment plant (WWTP) in Belgium a project is currently running whose aim is to demonstrate the application of process control to a full-scale industrial WWTP. In this paper we assess the potential benefits of applying this control to the plant.

The process under study is an industrial wastewater treatment plant with an average influent flow of 2700 $m^3.d^{-1}$. A characteristic of the WWTP is that the influent concentration of COD is extremely high (in the range of 6000 $mg.L^{-1}$ with peaks of more than 10 000 $mg.L^{-1}$) and can vary dramatically over time because of the batch-wise production of different products in the industrial plant. The reason for the project was that at that time a significant increase in production at the industrial plant was planned. It was expected that this would increase the load on the plant by 35%. Given that the existing WWTP with the current load often exceeded licence agreements with the current load at significant monetary cost to the plant, it was deemed necessary to make considerable improvements to the current plant.

The proposal was made to optimise the plant with the application of minor process changes and process control. Each of the unit processes was analysed individually to determine potential methods of optimisation. Some minor process changes were suggested such as the addition of phosphorous to remove the phosphorous limitation in the activated sludge system. The control system at the time consisted of the use of laboratory analyses and some on-line measurements, combined with some local, mostly manually operated control loops. Obviously, significant potential for control existed.

Figure 1 gives an overview of the units in the process and highlights the units that were focused on in the project in terms of process upgrades and the implementation of process control. Control algorithms have been developed for the units indicated. They have yet to be implemented.

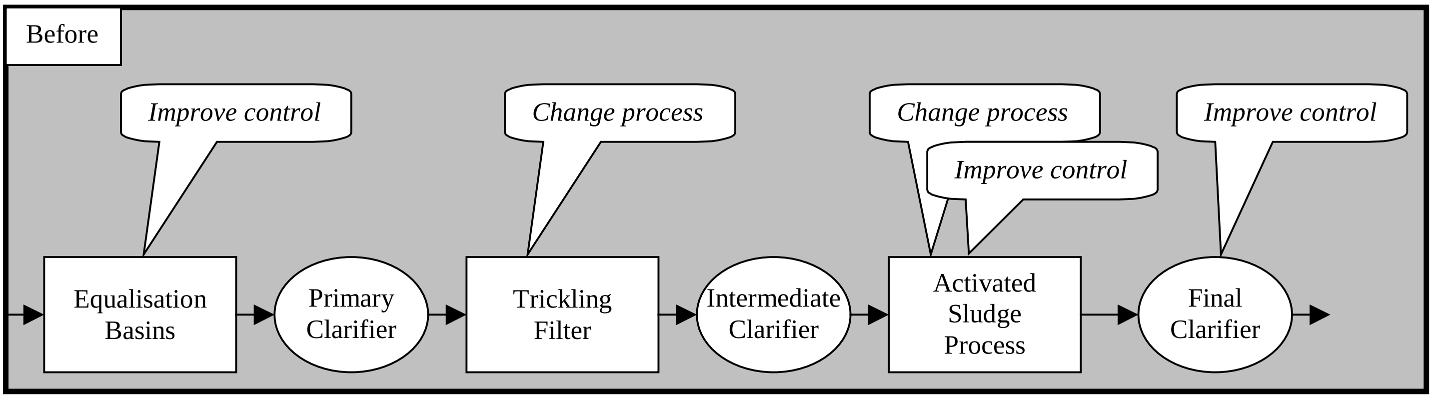

Figure 1. The plant flowsheet with the areas that the upgrade focussed on

A methodology for performing a control benefits study was introduced to the WWT industry by Lant and Steffens in 1998. This methodology takes a global approach to determining how to improve the process. As opposed to focusing on the individual units as was originally done, it also determines whether it is worth upgrading the process. It has not previously been performed on a full scale WWTP.

In this paper, the methodology is described, demonstrated and evaluated. We asked the questions:

1. "Will the benefits study give the same results as the analysis that was done originally?"
2. "How useful would the benefits study have been at the beginning of the project?"
3. "How important is it to use it now to assess the current status of the project and whether we are going in the right direction?"

THE PROCESS CONTROL BENEFITS STUDY

Most control engineers in the process industries agree that the effective use of advanced process control offers real benefits. However, control upgrade projects still need to be individually justified. They have to compete with other process improvement opportunities for their share of investment funds and access to finite skilled people resources.

In 1987 the Warren Centre for Advanced Engineering at the University of Sydney (Australia) developed a "Process Control Opportunities and Benefits Study", which has been extensively applied by many process companies around the world. However, this methodology to estimate the potential benefits of improved control takes time to perform, requires specialist control expertise and an up-front investment of 1-2% of the final project cost.

Aware of this, ICI (*Imperial Chemical Industries*) recognised the need for a simple and cheap means of determining a preliminary evaluation of control system performance, which does not require specialist control expertise to complete (Brisk and Blackhall, 1995). They developed a benchmarking procedure that enables us to 'measure' our process control practice against objective standards (in this case, world-class performance) and that highlights potential control opportunities and benefits. Especially in the field of wastewater treatment, where operators generally do not have process control expertise, a simple bench-marking procedure can direct decisions about the improvement of process control (Lant and Steffens, 1998).

How to perform the study

The method consists of three major steps, the completion of the Process Control Self-Assessment Proforma (Brisk and Blackhall, 1995), the estimation of potential monetary benefits of improved operation and the assessment of the potential of process control.

The first step, the completion of the Process Control Self-Assessment Proforma, forms the basis of the benchmarking exercise. The proforma is used to assess the current level of process control on the plant in comparison with world best practice in the processing industries. The questions do not require expert process control knowledge and may be completed by any engineer, or skilled operator, who is familiar with the plant. They relate to specific questions about the number of control loops, their level of sophistication and perceived performance.

A numerical value is given to each answer depending on its relationship to world best practice. An average value is then calculated. This "control system performance index" can now be used to rank the status of a plant's process control systems and their performance in terms of best practice. This index is used to place a plant in a category as listed in Table 1. A poor ranking could be used as an advice for applying a more thorough method of analysis, such as the Process Control Opportunities and Benefits Study. Analysis of the results of the individual questions indicates the targets for process control improvement that need more attention.

Table 1. The meaning of the ratings of the Self-Assessment Proforma (Brisk and Blackhall, 1995)

Index	Division	Exploitation of the technology
0-20	POOR	Neglecting the potential of well-proven available technology
21-40	BELOW AVERAGE	Applying proven control technology reactively
41-60	AVERAGE	Applying control technology developments reactively
61-80	GOOD	Applying proven control technology proactively
81-100	EXCELLENT	Leading control technology development proactively

Having identified the scope for improvement in control technology, we now should ask "Is it worth it?". That question is addressed in the second stage of the benchmark process. This step aims to determine the potential benefits of improving process control. That is, what can be gained by improving process control? It does this by assessing the costs of operation and possible upgrades.

Lant and Steffens (1998) added a third step to the benchmark procedure. They introduced a simple statistical approach to examine the potential for improvement. That is, what can be gained, in terms of reduced variability, by improving process control?

Two criteria are used in this analysis (Shunta, 1995):

- The Process Performance Index (P_{pk}) relates the product (in this case, the effluent) variability to customer specifications (in this case, the customer is the legislating agency),

$$P_{pk} = \frac{specification - average}{3 \cdot S_{tot}}$$

  where S_{tot} is the standard deviation of the data under analysis.

- To estimate the best possible performance the Process Capability Index, C_{pk}, is used,

$$C_{pk} = \frac{specification - average}{3 \cdot S_{cap}}$$

  where S_{cap} is the smallest standard deviation possible. It is estimated by differencing the data and calculating the standard deviation of the resulting data set.

To summarise, P_{pk} indicates how well the current controls are keeping the actual variability within the desired range, while C_{pk} represents the smallest variability achievable. Table 2 illustrates how to interpret the indexes.

Table 2. What do C_{pk} and P_{pk} tell us? (Shunta, 1995)

		Does performance meet capability?	
		No ($P_{pk} < C_{pk}$)	Yes ($P_{pk} \approx C_{pk}$)
Does capability meet specification?	No ($C_{pk} < 1$)	Change Process Improve Control	Change Process
	Yes ($C_{pk} >1$)	Improve Control	Little incentive for improvements

This process was applied to the wastewater treatment plant in question.

RESULTS

Step 1: Process Control Self-Assessment Proforma

The profile of the plant, as compared with world best practice, was determined given the operation and control strategies at the beginning of the project in 1996 (Table 3). The overall result is a score of 54%. This is an average rating and implies that the plant applies control technology reactively (Table 1).

Table 3. Benchmark profile of the Industrial WWTP *(A score of 5 is equivalent to World Best Practice)*

	Process Control Benchmarks	SCORE 0	1	2	3	4	5
Infrastructure							
1	*% stand-alone control loops* % of plant control loops not in a DCS or control computer	>95	80	60	35	20	**<10**
2	*Control loops per operator* Total No. of control loops on the plant divided by the No. of operators per shift	**≤10**	30	50	70	100	≥130
3	*Control loops/engineer*	≥750	500	400	300	200	**≤150**
Sophistication							
4	*Intermediate complexity control* % of control loops such as ratio, cascade, simple feed-forward	**0**	5	10	20	30	≥50
5	*Advanced control* % of control loops with techniques such as: dead time compensation, gain scheduling, self-tuning PID, inferential, model-based predictive control, expert systems	**0**	2	5	10	15	≥25
Measurements							
6	*On-line analysers* No. of on-line analysers divided by No. of sample points for lab analysis	0	0.25	**0.5**	1.0	5	≥10
7	*% On-line analysers used in closed-loop control*	0	10	25	50	**75**	100
Performance							
8	*% Control loops in manual*	**≥50**	20	10	5	2	≤1
9	*Poor control quality* % of control loops exhibiting undesirable characteristics, eg. overshoot, long settling times, oscillations, interactions	100	70	50	20	**5**	0
10	*Operator intervention* % of operator time spent resolving control-related problems	≥90	70	50	20	**10**	≤2
Performance Index		**54%**					
Ranking		**AVERAGE**					

In some respects, the plant is operating at world best practice. There are few stand-alone control loops, because most of them are integrated in a control system for data acquisition, data storage and analysis that uses commercial MMI (Man Machine Interface) software.

There are also few control loops per engineer. However, when we consider that the total number of control loops is low and the fact that they are mostly manual and consequently not very sophisticated, we see that in this respect there is a lot of opportunity for improvements. Also, the number of on-line analyses can be improved. If it is found that control on the plant must be upgraded, then these are the target areas for this.

Step 2: Potential benefits

The costs to the plant of the current operation are summarised in Table 4. They were estimated by the plant engineer. It is evident that the largest potential for cost reduction is in deferred capital expenditure (Question 1). This means that if the possibility for optimisation by control exists, it would be beneficial for cost reduction.

Table 4. Estimation of the potential benefits of the WWTP under study

Opportunity		estimated value/cost (relative to total yearly cost)
1. Is the plant operating at full capacity?	NO	83%
2. Do the effluent concentrations violate licence agreements?	YES	14%
3. Could the amount of additives be reduced?	YES	1%
4. Does the influent load change frequently?	YES	1%
5. Could the recycle be reduced?	NO	
6. Could the energy cost be reduced?	YES	1%
7. Could product inventory be reduced?	(N.A. to WWT)	
8. Is the frequency the effluent fails to meet regulations unacceptable?	NO	
9. Could the cost of effluent treatment/disposal be reduced? (e.g. sludge digestion/landfill)	NO	
Total estimated value of improvements		**100%**

Second to the savings from deferring capital expenditure is the cost of violating licence agreements (Question 2). This will increase as licence limitations are lowered within the next few years. Again, the potential for cost savings by process control is significant.

Step 3: Potential performance improvement

The third and last step in the benchmark procedure was to determine the potential for improvement as a result of reduced variability. Both the P_{pk} and the C_{pk} were calculated for a one-year data series from 1996, in order to see what those indexes would have been when calculated before the start of the upgrade project. The same was done with the most recent data available (1999) and almost the same result was obtained (Table 5). This was to be expected, because no significant changes in the treatment process or improvement in process control were made until the end of 1999.

For BOD, COD and SS, index C_{pk} is greater than 1, which indicates that the plant is capable of meeting objectives, but needs better control to do so ($P_{pk} < C_{pk}$). The other processes have a C_{pk} smaller than 1, indicating that the process is not capable of meeting specifications, even under good control. Another observation to be made from this table is that the average concentration of all pollutants in the effluent, except for ammonia, is far beneath the limits, even when the standard deviation is taken into account. The ammonia specification is violated.

Table 5. Evaluation of the actual plant

Parameter	Spec	Average	Stot	Scap	Ppk	Cpk	ACTION
BOD (mg.L^{-1})	950	107	102.0	52.0	2.76	5.40	**IC**
COD (mg.L^{-1})	1950	644	237.2	121.4	1.84	3.58	**IC**
TKN (mg N.L^{-1})	150	101	36.5	23.5	0.45	0.70	**CP+IC**
NH_4-N (mg N.L^{-1})	5	22	27.8	18.9	-0.21	-0.31	**CP**
SS (mg.L^{-1})	1000	64	59.2	48.9	5.27	6.38	**IC**
Ptot (mg P.L^{-1})	1	0.23	0.57	0.51	0.45	0.50	**CP+IC**

(CP = Change Process; IP = Improve control)

The main conclusions to be drawn from this evaluation table are that for the N (TKN and NH_4-N) and P (Ptot) removal a change in process is needed, while for BOD, COD and SS an improvement in control is sufficient. Concerning the control upgrade, an equalisation controller has been designed and simulated. With these results we can assess whether this controller provides sufficient improvement to the control of the process.

The effect of an improved equalisation control

When considering all the proposed controllers in the project, the equalisation controller is the one that can have the most significant effect on the removal of BOD, COD and SS concurrently. Recall that the plant has to deal with strong variations in influent flow and concentration. Therefore, the plant is equipped with three equalisation basins. An advanced controller was designed that optimises the performance of this equalisation using the volumes in the basins and the TOC concentration at the outlet as inputs. A Linear Quadratic (LQ) state feedback controller is used in order to damp variations in flow, while a simple P (proportional) algorithm takes care of the concentration fluctuations. In order to overcome difficulties with short and long term disturbances, a fuzzy-based supervisory system and a long time filter are added to the general control system (Harmand *et al.*, 1999).

The effect of an improved equalisation process can now be assessed. Simulations with the equalisation controller, based on real plant data, showed a decrease in variation for both flow and concentration of about 50%. Table 6 calculates the new performance indexes for the actual plant, assuming that the equalisation controller is operational. It shows that the equalisation of the influent indeed affects most of the processes that needed improved control. In other words, with only the equalisation controller implemented, the plant is capable of meeting the actual specifications. No further control improvement is required. The conclusion for N and P, of course, remains the same: change the process.

Table 6. Evaluation of the plant, assuming the equalisation controller is operational

Parameter	Spec	Average	Stot	Scap	Ppk	Cpk	ACTION
BOD (mg.L^{-1})	950	107	51.0	52.0	5.51	5.40	**none**
COD (mg.L^{-1})	1950	644	118.6	121.4	3.67	3.58	**none**
TKN (mg N.L^{-1})	150	101	18.2	23.5	0.90	0.70	**CP**
NH_4-N (mg N.L^{-1})	5	22	13.9	18.9	-0.41	-0.31	**CP+IC**
SS (mg.L^{-1})	1000	64	29.6	48.9	10.55	6.38	**none**
Ptot (mg P.L^{-1})	1	0.23	0.28	0.51	0.90	0.50	**CP**

(CP = Change Process; IP = Improve control; none = no action to be undertaken)

The effect of an increased load

At the beginning of the project a load increase of about 35% was expected. The potential for performance improvement was calculated for this new load, still assuming that the equalisation controller is operational

(Table 7). To estimate the effluent concentrations under the new load, the influent concentrations from 1999 were increased with the expected 35% and the removal efficiency for each of the pollutants was assumed to remain constant. No increase in influent flow is expected (only in concentrations), therefore the performance of the settler would probably not change significantly, which justifies the assumption that the suspended solids concentration remains the same.

As can be observed from the new calculations (Table 7), with an optimised equalisation control, the plant is still capable of meeting the specifications ($C_{pk} < 1$), even under increased load.

Table 7. Evaluation of the plant with the equalisation control and under the expected load increase

Parameter	Spec	Average	Stot	Scap	Ppk	Cpk	ACTION
BOD (mg.L^{-1})	950	144	51.0	52.0	5.27	5.17	**none**
COD (mg.L^{-1})	1950	863	118.6	121.4	3.06	2.98	**none**
TKN (mg N.L^{-1})	150	135	18.2	23.5	0.28	0.22	**CP**
NH_4-N (mg N.L^{-1})	5	30	13.9	18.9	-0.60	-0.44	**CP+IC**
SS (mg.L^{-1})	1000	64	29.6	48.9	10.55	6.38	**none**
Ptot (mg P.L^{-1})	1	0.31	0.28	0.51	0.81	0.45	**CP**

(CP = Change Process; IP = Improve control; none = no action to be undertaken)

It was assumed that the removal efficiency does not change under an increased load. However, it is likely that the efficiency will decrease. Calculations showed that, once the removal efficiency for BOD and COD drops below 80% of the original value, the evaluation indexes give the advice to focus on changing the process.

DISCUSSION

The benefits study has shown that, in order to cope with an increased load, the WWTP must undergo some process changes and control should be improved. This will dramatically affect the costs at the plant.

The results of the proforma indicate that in order to improve control more control loops may be required and they should be automated. This is comparable with the current project where it was decided that three control loops should be implemented and automated. The most important and sophisticated controller is the optimisation of the equalisation control. This controller, with the implementation of the necessary on-line analysers, moves the process control at the plant towards the current world best practice.

The study highlighted that for improvements in current operation, process control was required to reduce the variability of most pollutants. It also showed that process changes were required to improve ammonium removal. In the future, with the expected load increase and decreasing effluent limits, process changes would also be required in order to meet the other pollutant limits.

This can be compared with the original focus of the project. We consider again the flowsheet and the planned changes. How do they contribute to the optimisation required? Figure 2 summarises the contributions of the initially proposed changes to optimisation of the process. Now our first question, “Will the benefits study give the same results as the analysis that was done originally?”, can be answered. The benefits study indeed came to the same conclusions in terms of what to do. However, from the benefits study it appears to be more logical to test first whether the process change will sufficiently improve the process.

The second question asked about the usefulness of performing the benefits study at the beginning of the project. Although it didn’t replace the need for an individual unit analysis, the results of the study have given the direction in which this analysis should have been performed. This would have made the analysis more efficient and would have inspired more confidence in it. To answer the second question, the study has proven to be a useful tool at the beginning of an upgrade project.

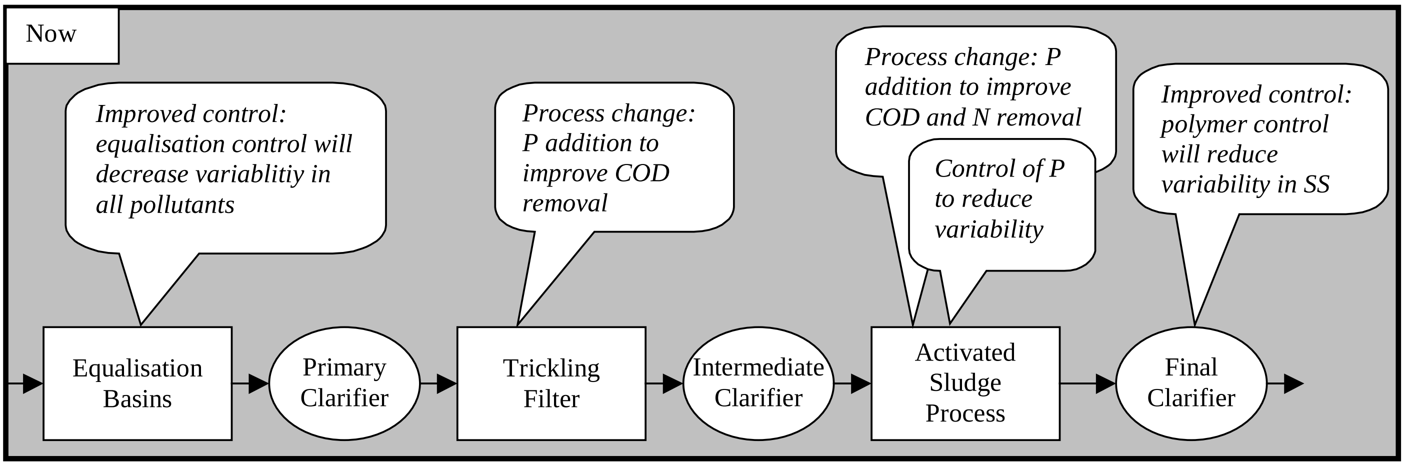

Figure 2. The expected results of the plant upgrade

This brings us to our third question, "How important is it to use the benefits study to assess the current status of the project and whether we are going in the right direction?". The study showed that the equalisation control performs well. Even for the increased load it obtained good results with a removal efficiency of more than 80% of the original. At this point the knowledge about the effect of the process change becomes important. It can be assumed that, since the COD to N ratio in the influent is only 100:2.7, it should be possible for the biomass to take up this nitrogen if the microorganisms are healthy. The biomass suffers from a P limitation. Addition of P will make it healthier and it may be possible to take up more N and COD. However, we have no proof of this effect so far. The study indicates that this should be the next focus in the project.

CONCLUSIONS

In this paper we describe, demonstrate and evaluate a method for control benefits analysis. The aim was to determine the benefit of using the method before and during a control upgrade project. This was done by applying it to a full-scale industrial WWTP that is currently undergoing a control upgrade and by comparing it to the method that was originally used. The method is quick and easy to perform. It is a useful tool at the beginning of an upgrade project. Although the study does not replace the need for a more thorough analysis, it can point out the target areas for this analysis. The results also proved its value as a periodical evaluation method, because it can be used to redirect the project as new data become available.

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