Implementing an Intelligent Operations and Asset Management System that Integrates DCS, SCADA, CMMS and Process Models for Activated Sludge, IFAS and Biofilms to Improve Compliance and Optimize ENR Plants in Real Time

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ABSTRACT

This paper discusses the development and application of a whole plant simulation and control system for simultaneous optimization of processes and assets. It overcomes several limitations in Distributed Control Systems (DCS) and SCADA systems, as implemented today in ENR plants for local optimization of secondary treatment, tertiary treatment and solids handling. It does so by placing a whole plant optimization system that is asset based as an operating layer on top of local optimization routines, thereby enabling global optimization of asset usage over time and operation across the whole plant. The system can be implemented to provide intelligence to DCS to improve and optimize the operation based on current condition of assets and the availability of tanks in each part of the plant. Additionally, it provides intelligence to asset management software to help prioritize corrective and preventive maintenance, based on real time computation of risk and risk reduction through redundancy following optimization. The mathematical techniques for solving linear and non-linear partial differential equations associated with biochemical and physico-chemical reactions in tanks were upgraded to improve their accuracy to reflect actual operating conditions as measured with sensors and to improve their speed to run over 100 optimizations of the whole plant within one minute. Implementation of the tools can help the plant improve compliance, especially during periods when the plant is subjected to stresses from wet weather flows and extreme temperatures. In the long run, the Utility is able to manage its plant at lower operating, maintenance and life cycle costs while meeting its permits.

KEYWORDS

ENR, Water Reuse, Real Time Optimization, SCADA, CMMS, Minimize Operating Costs, Life Cycle Costs

INTRODUCTION

The water and wastewater industry has made significant investments in Distributed Control System hardware and software (DCS), SCADA and computerized maintenance management systems for managing work orders. As a result, most medium and large plants are equipped with sensors and control logic to optimize each system in the plant. Examples include sensors and control loops for the secondary treatment system, tertiary treatment system and digester system. What has been observed at some plants is that in the absence of real time optimization based on biochemical and physico-chemical pathways, these local control systems cannot be operated in a manner such that the setpoints also achieve global optimization of resource needs (chemical feeds, energy), equipment and tank usage across the whole plant. Certain plants and industries, such as the cement manufacturing industry, have tried to implement fuzzy logic and neural network systems for global optimization. These work well when the biochemical pathways are simple (linear instead of Monod, limited competition between species of bacteria, limited influence of one reaction on another); the logic patterns itself on past behavior observed in response to various operating conditions and uses this to predict expected behavior in response to future conditions. What has been observed at several types of plants is that while each control system can improve the operation of the specific part of the plant which it is controlling, there is no additional logic that looks at how the kinetics of a downstream process are affected by removals and releases in an upstream process, a sidestream process and a dewatering process. The neural networks are unable to work through all conditions observed in biochemical systems.

In 2010, the Maryland Department of the Environment (MDE) identified the need for such a global plant optimization system because the efficiency of denitrification filters that were being funded by MDE as part of ENR upgrades was apparently constrained by the mode of operation of secondary treatment processes upstream and by the management of recycles from solids dewatering. There have been some instances where an ENR plant was using all of its denitrification filters in winter to treat 60% of the flow. Other plants were removing less than 1 mg/L of nitrate-N instead of 3 to 4 mg/L during wet weather flows. The problem was compounded when the secondary treatment system lost some of its ability for simultaneous nitrification and denitrification in the aerobic zone and discharged a higher nitrate-N load. In response, plants began to use all the available tanks in the secondary treatment system to maximize nutrient removal in the secondary treatment system to overcome constraints within the denitrification filters. In some instances, the biomass in the filters was operated at near starvation modes for extended periods of time because of lack of nitrates, which limited the biomass available when the flows increased and the temperatures decreased.

Further analysis of the plants showed that tertiary unit processes were operating at lower efficiency because the control logic in the secondary treatment system was based on BNR. During BNR, the plant did not have a tertiary nitrogen removal system. As a result, the logic was geared to maximize nutrient removal in the secondary treatment system. This could generate conditions that resulted in poorer performance of the tertiary system. Unfortunately, other than adding supplemental phosphoric acid, no other approaches were proposed by the vendors of the denitrification filter or by the controls engineer to jointly manage the secondary system in concert with the tertiary system. The result was excessive use of the assets at all locations, leading to reduction in their life cycle cost and reduction in the capacity of the assets.

Similar problems and opportunities for improvement with global optimization were observed at several other types of plants. In some plants, this has the opportunity to generate significant savings in life cycle costs over a 20 year period (summed total of operation, maintenance and asset replacement costs). These included:

1. Plants with dual anoxic zones for ENR and biological excess P removal (Bardenpho, modified Bardenpho), in which there could be opportunities to optimize between bio-P removal and nitrogen removal and dosing of supplemental chemicals used for supplemental carbon and P removal under normal and wet weather.

2. BNR plants to which denitrification filters were added for ENR, where the operation of the secondary and dewatering could be optimized in concert with the denitrification filters (discussed above). At a 25 MGD (100,000 m3/d) ENR plant with denitrification filter, one could expect savings in excess of 2 Million dollars with the right type of optimization and asset management over a 20 year period.

3. IFAS plants where the operation of media could be optimized by managing aeration, air scour and hydrodynamics around biofilm media, both under normal and wet weather conditions. The system could be used to control organic carbon and ammonium-N concentrations at different points along the IFAS tank to increase the efficiency of biofilms in carbon removal, nitrification and denitrification, thereby increasing the efficiency of IFAS plants. It could also be used to manage the washout of biomass or media during extreme flows.

4. Membrane plants where the membrane operating and replacement costs could be reduced substantially by managing the operation of the rest of the plant to minimize the need to use the most expensive part of the plant, which is the membrane tanks and equipment. This can lead to very significant savings in excess of 5 Million dollars in life cycle costs over 20 years at a 25 MGD plant (100,000 m^3/d) based on experiences at several membrane plants.

5. Plants with primary clarification, nutrient removal and anaerobic digestion, where the organic carbon sent to the anaerobic digesters could be increased at all flows (normal day to wet weather) by as much as 10 percent by increasing the number and condition of primary clarifiers in operation. In some cases, this could be achieved with chemically enhanced primary treatment. By controlling the primary sludge thickness together with this increase in removal, one could increase digester gas production and cogeneration. The whole plant optimization would then be used to simultaneously manage the variation in nitrogen recycle loads on a day to day basis to maintain reasonable carbon to nitrogen ratios in the secondary treatment, and improve the nutrient removal at lower DO setpoints with less aeration energy. This would help move such a plant towards becoming self-sufficient in energy. In this instance, the additional revenue generation from gas production together with savings from aeration could exceed 4 Million dollars over a 20 year period at a 25 MGD plant (100,000 m^3/d).

6. Plants located in tropical and equatorial climates, where liquid temperatures vary from 25 to 37 C, the changes in the real time operating mode made through the optimizer could maximize conversion of ammonium-N to nitrogen gas. This could be done through simultaneous organic carbon removal, nitrification and denitrification in the biofilm of IFAS and in the flocs of the aerobic zone of the activated sludge basins. It can be done by modulating the DO to between 0.25 and 1 mg/L. It can also be done by increasing the conversion of ammonium-N to nitrogen gas under low DO and low nitrate conditions in early sections of the basin, especially when biofilm media is used.

CHALLENGES

The approach to solving this problem for ENR plants turned out to be far more complex than originally envisioned in 2010. Unlike design models based on activated sludge and biofilm processes, optimization of the plant required analysis of the asset utilization to improve their capacity, reduce their operating cost, and reduce the replacement cost. It required evaluation of the processes in real time to identify if there were ways to make the plant and asset utilization financially more efficient by looking at the entire plant and all its processes and assets, rather than a portion of the plant, a particular process, or particular piece of equipment such as a pump, or a particular alternative for a chemical such as methanol versus Micro-C, or Poly Aluminum Chloride (PACl) versus Alum. It required improving the accuracy of the computations to accurately reflect effluent quality, sludge production, aeration and gas production and speeding up the calculations to analyze over 100 combinations of operating conditions across the whole plant in one minute. Further, this had to be done using actual biochemical pathways rather than simplified non-Monod based kinetics.

What was challenging is that such optimization had to look at the biochemical and physico-chemical pathways in near real time to evaluate the response of downstream processes as the flows and loadings change. This required enhancement of the mathematical techniques used to solve the differential equations based on ASM2d and biofilm models that represent Monod equations, and speed up the calculation and improve the accuracy to reflect actual operating conditions. Additionally, there were considerable challenges in extracting data packets in real time from SCADA. For each sensor, the technology had to have a secondary mechanism to verify if the sensor data received in real time was sufficiently accurate to avoid optimization to false readings of DO, flow, temperature, etc. This required verification against the primary reading from the sensor, and in some instances backup values generated through computations. The primary reading could be the equipment operating status, such as for a pump, which was verified against a sensor reading. A simple example is a method of detection if a pump is on but flow sensor reading is very low; or when two pumps are on but the sensor reading exceeds a rational maximum value of capacity for those two pumps. In other instances, the computed value from the process model had to be analyzed against the actual value, such as for a WAS sludge pump, to determine if the pump reading made sense based on the operating MLSS and sludge hauled from the plant.

METHOD

The general approach towards optimization is to provide intelligence to the plant's Distributed Control System (DCS) such that it can optimize the operation based on current condition of assets and availability of tanks, and from operating data from the DCS system, laboratory and inspections. The technology provides intelligence to maintenance management and asset management software to help prioritize corrective and preventive maintenance. The optimization routines also look at the risk and risk reduction through redundancy, which are based on principles outlined by IIMM (2011). The optimization routines and the generated recommendations help manage those risks and help the plant lower life cycle costs.

Managing Process Operations in Real Time based on Time Dynamic Computation of Risk

<u>Graphical User Interface (GUI) designed with Flexibility required for Plant Operations</u>

A key feature is the ability to depict and change configurations automatically in the GUI when changed in the plant and communicated through DCS. For example, if a plant switches from using one blower system for its aeration tanks to two different blower systems (as in Westminster, Maryland, where the North trains and South trains can be operated with two separate blower systems or with one blower system), the simulator should be able to automatically assign the correct blowers to correct tanks by extracting this information from the DCS. Alternatively, when a particular part of the plant does not feed its data to the DCS, the operator has to be able to implement this by checking or unchecking boxes in the operations menu built in the graphical user interface of the software. Thus, it eliminates the need to create or load additional plant configurations.

What this required is an asset management structure to represent assets that affect the plant's behavior within the simulator. This was done through the Asset Explorer shown on the right hand side of Figure

1. Each asset is built into an intelligent hierarchy. The hierarchy is customized to each plant and Utility enterprise. An example is in Table 1. It is based on a comprehensive understanding of how the operation of an asset affects its parent system. This hierarchy need not be the same as in the CMMS system. This is because in most plants, the CMMS system is not based on an intelligent asset hierarchy built around how risk and impact transfers up from the equipment to the plant and enterprise. As an example, through an intelligent hierarchy, one can determine and compute how the operating status of a particular pump in the RAS system would affect the RAS system, the clarifier unit process sitting as its parent, the secondary treatment system sitting as its grandparent, and the plant sitting as its great grand-parent. A RAS pump would not be located in the same part of the hierarchy as a nitrate recycle pump or a primary sludge pump; it may not be located in the same part of the hierarchy as a waste sludge (WAS) pump even though the WAS and RAS may be physically located in the same building unless the failure of the waste pump leads to disruption in the operation of the clarifier.

Real Time Optimization and Feedback using Multiple Solvers

A second feature is the higher speed and accuracy required for simulating time dynamic actual conditions such that they can be used for optimization, as opposed to periodic analysis for design conditions or occasional analysis to verify and change operations. The algorithms created use the 64 bit architecture in new processors and use multi-thread and parallel computing for bioreactors to speed up computations. Typically, more than 81 combinations of operating parameters have to be run within 1 minute and repeated every 15 minutes. The operator feedback screens have summary tables that display key data such as DO, Soluble BOD_5, Soluble biodegradable COD, VFA, NH_4N, SKN, NO_2N, NO_3N, OP, and MLSS (Figure 2a). This feedback is customizable to each plant and its operations. It is different from the tables and graphs generated for the process engineer; also, these are different from those used for design. Additionally, it can include parameters that can be measured by sensors to compare values to sensors at specific locations; it can also include parameters such as Soluble BOD_5 and VFA that are not available through real time sensors.

To provide flexibility to run analysis to troubleshoot processes, plan future operating conditions or conduct analysis for asset management, the software platform was constructed such that the plant could run the software using multiple parallel solvers. Table 2 shows 8 combinations which can be run in parallel. For example, the operator can be running one thread on real time to continuously optimize the plant; he/she can run another in off-line mode to analyze one or more future conditions expected over next 24 hours or the next month. This is done through the Scenario Manager. The Scenario Manager creates a replica of the current setup of the whole plant for the latest condition and allows the operator to conduct scenario analysis.

Table 1: Typical Asset Hierarchical Structure for a WWTP (additional class - sub class structure of each asset is not shown)

Asset Level	**Asset Description and Examples**
Enterprise	Name of Utility, not shown in the plant but shown in the database
Plant	Name of Plant – can be water plant, wastewater plant
Treatment System	Headworks; Primary; Secondary, Tertiary, Solids Dewatering
Super Groups (if required)	Named Super Groups of Trains (eg: North & South, Old and New)
Unit Process	Raw Influent, Screens, Grit Chamber; Bioreactor (Anaerobic, Anoxic, Aerobic) Secondary Clarifier
Tank Groups; Diffused Aeration; Pump Systems; Flow Controllers	Tank groups under Unit Processes such as: Grit Chamber; Bioreactor; Secondary Clarifier; Pump Groups in Unit Processes; Diffused Aeration in Aerobic Cell
Tanks, Pumps, Measuring Devices (Sensors, meters)	Individual tanks (Grit Chamber 1, Tank 1 dimensions for Anaerobic Cell, Tank 2 of Anaerobic Cell); individual pumps (RAS pump 1); DO control instruments

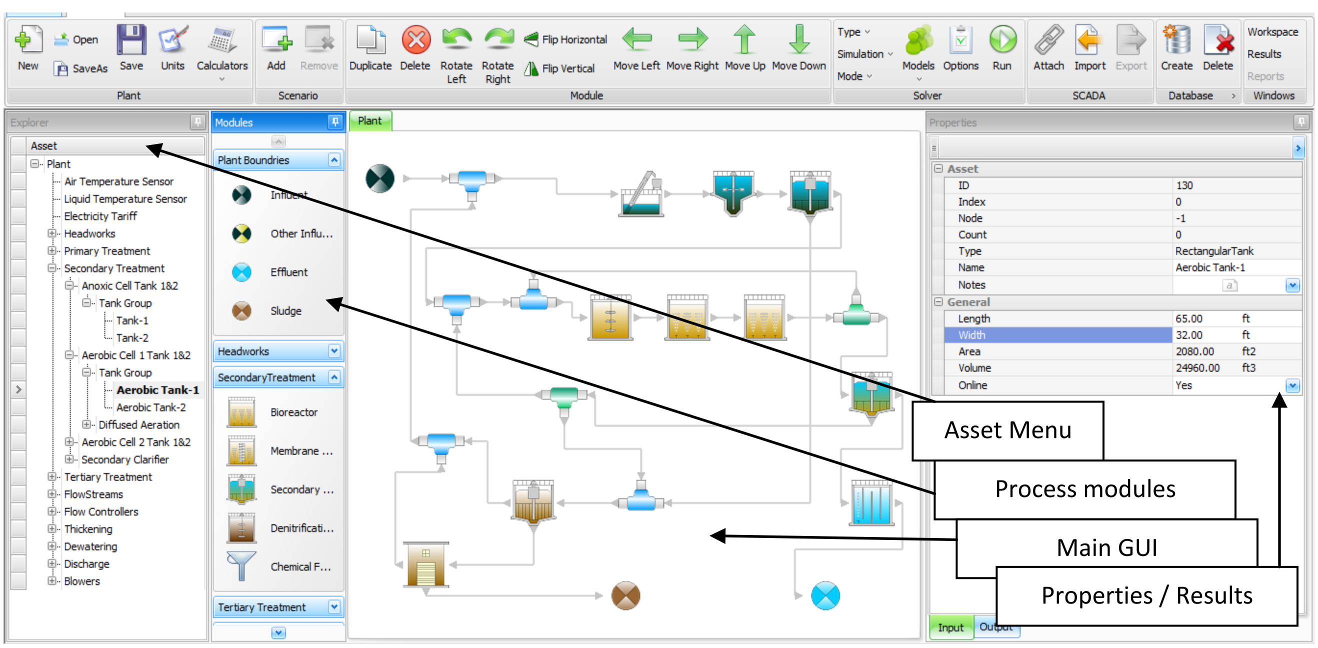


Figure 1. Application of Complete Asset Hierarchical Structure to Communicate with Process and Asset Management Models (Screen shows Asset Menu and Modules to the left of GUI, Properties and Results menus on the right).

Table 2: Running parallel solvers within the simulator (up to 2 x 2 x 2 = 8 parallel solvers can be used)

Simulation	Steady State	Dynamic
Application	As an Assistant (Analyze future operating condition or a design condition)	As an Optimizer (Analyze multiple combinations of DO and recycle rates on the latest steady state and dynamic simulations) Optimizer selects the best operating condition out of those alternatives that pass certain thresholds. The thresholds are specified in a menu used to define operating conditions
Operating Mode	On-line (real time) Optimization is done on the latest time step	Off-line (for scenario and future condition analysis) Typically run for a 24 hour period. Optimization is done on the last time step after running all the time steps over the 24 hour period

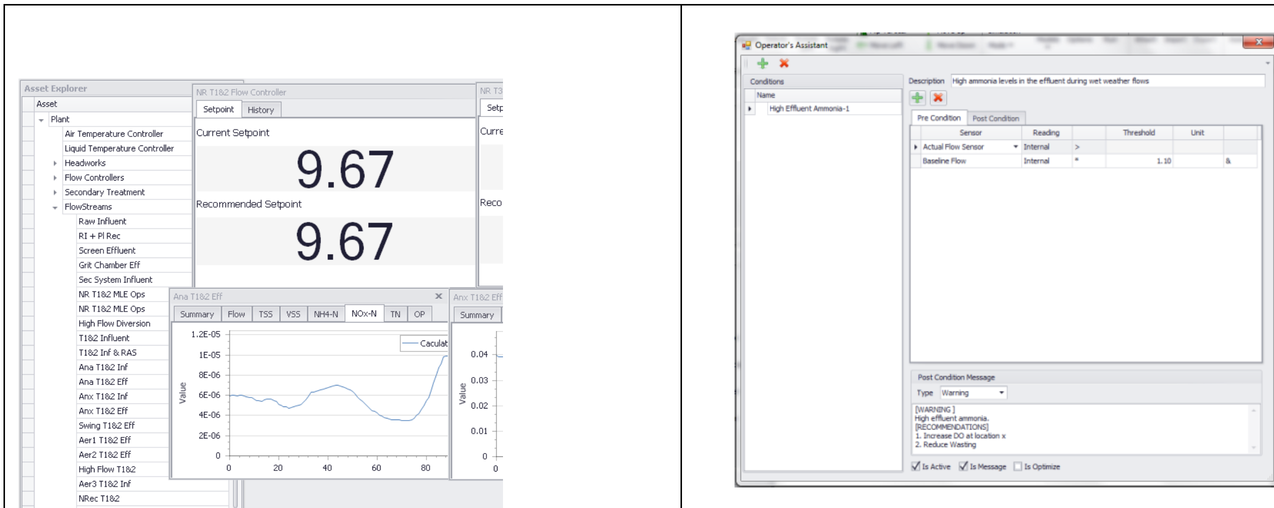


Figure 2. Additional Interfaces and Displays

Figure 2a. Dashboard Display for the Operator (Above Left)

Figure 2b. Interface to set up Thresholds in the Artificial Intelligence Routine (Above Right)

<u>Real Time computation of Reduction in Risk through Redundancy</u>

A third feature that is not available in any asset or computerized maintenance management model is the ability to track the capacity of blowers and pumps individually as assets based on their operating condition; then use the actual capacity as an input to the process optimization routine, rather than design capacity; and then apply the results of real time optimization to compute the real time risk reduction due to redundancy.

It is important to understand that as part of the installation and configuration, the inspection protocols are upgraded such that the actual capacity of tanks and equipment are measured, and the links are set up for the software to know which pieces of equipment and tanks are available for service. Providing the plant staff with the knowledge to do a condition assessment to determine the actual capacity is part of the technical support. Such assistance is customized for various types of moving equipment such as types of pumps, blowers, mixers and drives; it is also provided for diffuser systems and tanks. It is based on a comprehensive understanding of methods to conduct operational condition assessment of equipment and tanks. This skill set is very different skill set from writing computer code or doing a design. It is the key to correctly setting up the software to operate and manage the assets in a plant. A team that has expertise in operations and asset management does the implementation.

The computation of risk and risk reduction due to available redundancy is done in real time, both before and after optimization. Obtaining the two values of a setpoint, such as DO or wasting rate, before and after optimization is important. When the complete asset management system is implemented together with the plant operations element, from an asset management perspective, one may be able to use the optimizer to find ways to operate a plant in a manner that is financially more efficient. A simple example is an activated sludge system at an ENR plant that is operated at a lower MLSS, with fewer clarifiers and with lower doses of chemicals added for P removal. This can help simultaneously improve the performance of denitrification filters by increasing the nitrate level slightly to prevent periodic starvation of the biofilm. Another example is based on observations at several MBR plants. Optimization can show that one is able to operate a MBR plant at a lower MLSS and improve the oxygen transfer efficiency, which can help reduce the number of MBRs in operation and reduce the amount of nitrates generated through lysis of biomass and conversion of ammonium-N to nitrate-N in the MBR tank, thereby improving the effluent total nitrogen. Reducing the number of MBR tanks in operation helps reduce the life cycle cost of the part of the plant that may be the most expensive to operate per gallon of wastewater treated.

The optimization routines help determine a more accurate value of redundancy in real time and magnitude of risk reduction due to redundancy. Unlike static asset management models, where the asset management team sets up the formula for risk reduction upfront without means to optimize the rest of the plant in real time, the software component optimizes the plant in real time; as a result, the redundancy is tracked in real time and is more accurate. Rather than use a set of static values for risk when one or two blowers are out of service for maintenance, in this instance one optimizes the rest of the plant to see if the aeration demand can be reduced when a blower is out of service, thereby still achieving the required redundancy. If the optimization indicates that such redundancy is not available, it is a true measurement of risk and such work has to be prioritized over work on other equipment in systems where the redundancy can be created through optimization. Further, the optimization is dynamic, it responds to the actual tanks and equipment available and the redundancy desired. Warnings are generated when redundancy drops below user accepted thresholds. Warnings are also supplemented with information if there are pieces of equipment that are out of currently out of service whose work order could be prioritized to achieve the level of redundancy.

In summary, the process model functions at the asset level and provides intelligence not just to the DCS and SCADA operator based on its analysis of what optimum setpoints should be; it provides feedback and intelligence to persons writing work orders in computerized maintenance management systems such as Maximo, Synergen, CASSworks RJN, etc, as to which tank or equipment to put back in service in what priority. This offers real time computation of redundancy and risk in the plant to manage assets based on IIMM (2011; 2006 INGENIUM, New Zealand).

Biochemical Processes

The biochemical processes in the software enhance the ASM2d Model for activated sludge systems; biofilm processes models for IFAS and biofilm systems, and anaerobic digestion models for biochemical and physic-chemical processes in anaerobic digesters. Note that all chemical and biochemical processes operate simultaneously in all tanks.

The processes capture nutrient removal, GHG and Nitric Oxide Emissions. The simulator conducts a complete GHG simulation. The nitrification is simulated as follows: oxidation of NH_4 to NO_2 by AOB, followed by oxidation of NO_2 to NO_3 by NOB. Additionally, it allows for denitrification by *N Europea* from NO_2 to NO, N_2O and N_2. The heterotrophic denitrification is broken up into four steps for ordinary heterotrophs (OHO) and polyphosphate accumulating bacteria (PAO) to go from nitrate to nitrite to nitric oxide to nitrous oxide and to nitrogen gas (Lodhi *et al*, 2010). The physico-chemical portion of the model includes equations for diffusion of NO_2 and NO into the atmosphere. These equations are also related to the type of aeration and mixing. Unlike ASM2d, which uses the same coefficient for several reactions, the simulator uses a larger number of coefficients to improve calibration, such as the ability to specify different half saturation constants for DO (K_{DO}) for fermenters, Ordinary Heterotrophs (OHO) and Poly-phosphate Accumulating Organisms (PAO) under aerobic conditions, OHO and PAO for inhibition under anoxic conditions, and each step of AOB nitrification.

RESULTS

Easton, Maryland

The Easton WWTP in Maryland was the first to receive an ENR permit in the Mid-Atlantic region. The plant has an annual ENR permit of 4 mg/L for Total Nitrogen and 0.3 mg/L for Total P. It is a Modified Bardenpho system (Figures 3 and 4). The conditions experienced during high flows are shown in Table 3. During this period, the normal flows were 2.2 MGD (8000 m3/d). These levels for Total Phosphorus were exceeded during high flows. One of the possible reasons for the change in Biological Excess Phosphorus Removal is the reduction in volatile fatty acid production in the sewer system during high flows.

For the Easton application, the simulator was operated with the Scenario Manager to analyze possible changes that occurred during high flows. For real time operations, it is being set up to receive influent or effluent flow readings and operate off of either. This data can then be applied at 15 minute intervals to run up to n (n = 96 is default) dynamic combinations for dynamic simulation in 15 minutes. Additionally, it can run up to n combinations of variables such as changes in sludge wasting rates on operating MLSS every 24 hours by rerunning the steady state model for the current operating temperature and loads. The operator sets up thresholds of performance in the Artificial Intelligence (AI) Routine (Figure 2b). These thresholds are then used to determine the best operating combination of operating setpoints for normal and high flows.

Table 4 shows five scenarios out of 96 combinations that can be simulated. This analysis, shown as a series of discrete simulations, can be performed every 15 minutes to help identify how to reduce effluent OP from 1.3 mg/L to 0.3 mg/L during high wet weather flows. In this instance, the Optimizer managed the following variables simultaneously: nitrate recycle rate, DO at each of two locations in the ditch, glycerol feed and Aluminum Hydroxide or Poly Aluminum Chloride (PACl) feed for chemical P removal. Within the AI routine, the operator is allowed to give a preference to avoid certain solutions as the primary mode of operation. In this case, based on experience, it was decided that solutions that required switching to Aluminum Hydroxide or PACl would be given lower priority based on previous experience which showed that switching the plant to chemical P removal would require a long time period to recover the desired level of BEPR. Instead, the Scenario Manager helped discover a better strategy. First, the DO setpoints in the ditch would be lowered with flows, allowing ammonium-N to increase to a wet weather threshold. Simultaneously, the nitrate recycle rate would be lowered. The advantage of lowering the nitrate recycle is a larger anaerobic zone for fermentation in the anoxic cells (Figure 4). While this increases the effluent NO_3N, the simulator overcame this by reducing DO set points until ammonia begins to increase above 0.2 mg/L, following which it asked for glycerol addition to the post anoxic cell, which helped reduce NO_3N and reduce nitrates recycled to the anaerobic cell with the RAS. This mode of operation can help sustain BEPR through high wet weather flows (Table 4). The actual rate of change of DO, nitrate recycle and supplemental carbon flows would be managed by the Optimizer. Additionally, the Optimizer looks at the values from the ammonia sensors in the ditch to check that it is within reasonable calibration.

Table 3. Actual Problem as Observed at Easton WWTP, MD

	Temp	Flow	OP	NH4N	TN
Jul 1 to Aug 10 2009	22	2.1	0.2-0.3	0.1	2.9
Aug 21 to Aug 30 2009	23	3.0 (peak 4.3)	0.6 – 2.0	0.1	3.0

Note: In Sep 2009, plant started feeding chemicals for P removal. It took over a month (Sep 2009) to recover BEPR.

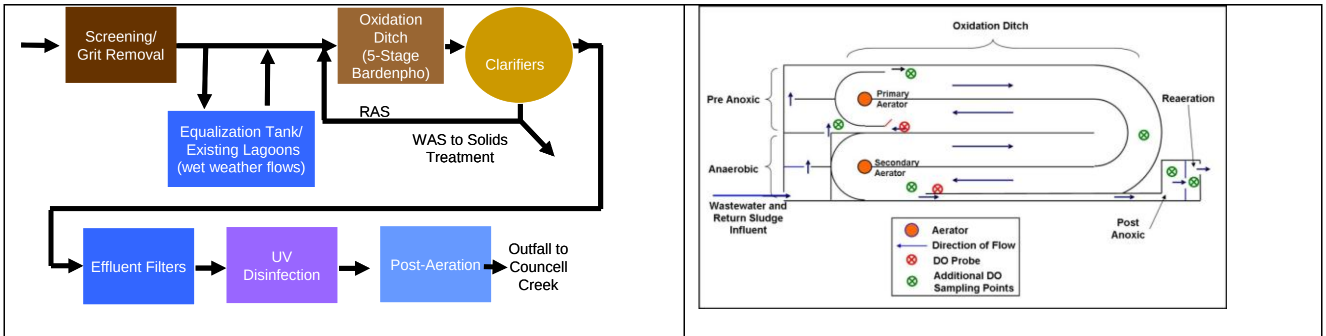


Figure 3. Layout of Easton Plant, Maryland, USA. 16,000 m^3/d plant operating at Average flow of 8100 m^3/d in 2009

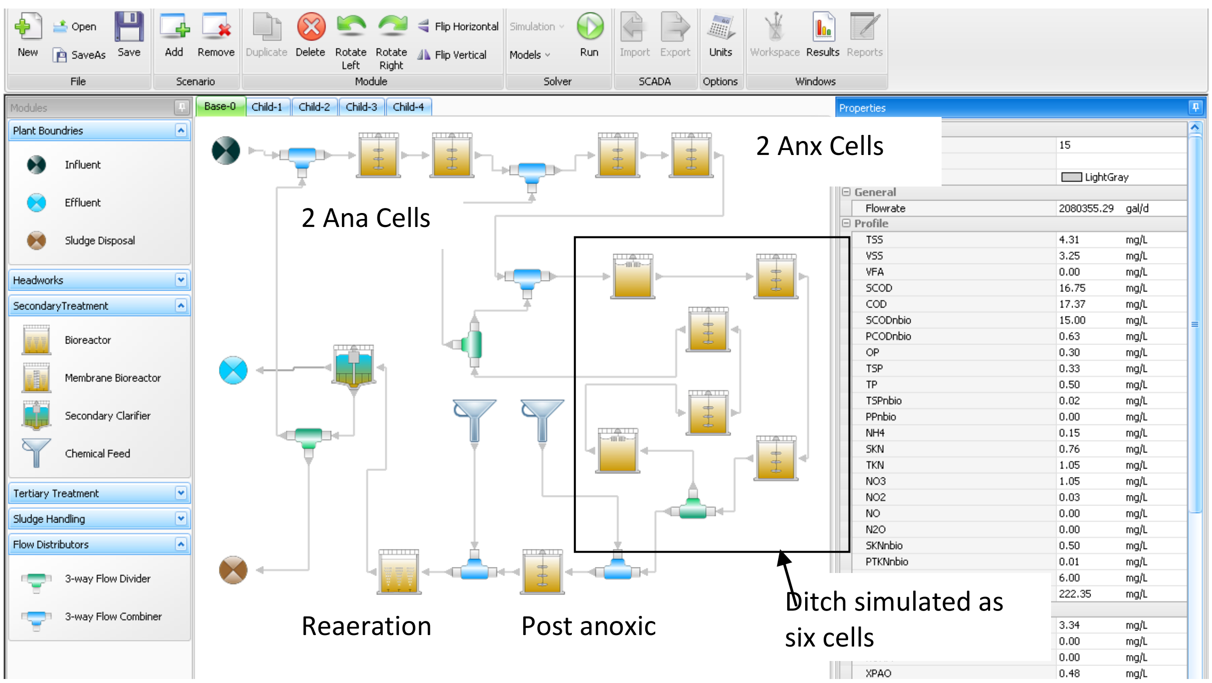


Figure 4. Plant has 2 anaerobic cells receiving RAS, two anoxic cells receiving nitrate recycle from ditch, ditch (simulated as follows: aerobic with Eimco mechanical aerator, anoxic, anoxic, aerobic with Eimco mechanical aerator, anoxic, anoxic), post anoxic with optional glycerol feed, reaeration with optional Aluminum Hydroxide feed, Clarifier.

Table 4. Application of Controller for Scenario Analysis and Control of BEPR during High Flows at Easton, MD

Optimization of BEPR and Nitrogen Removal is achieved by Simultaneously Controlling Nitrate Recycle, DO at two locations in ditch and Glycerol Dosing – analysis shown at 12 C – winter low MLSS Temperature in 2010

							Secondary Effluent before filtration				
No	Scenario	Flow	Nitrate Recycle	DO Ditch Loc 1	DO Ditch Loc 2	Glycerol	NH4N	NO3N	TN	OP	TP
		MGD	Q	mg/L	mg/L	LPD	mg/L	mg/L	mg/L	mg/L	mg/L
1	Normal Flow	2.1	14.7	0.8	1.0	0	0.15	1.05	2.13	0.30	0.5
2	High Flow	4.3	14.7	1.0	1.1	0	0.15	1.33	2.22	1.31	1.43
3	High Flow	4.3	7.4	0.7	0.7	0	0.18	2.31	3.27	0.85	1.0
4	High Flow	4.3	4.3	0.7	0.7	0	0.21	3.14	4.12	0.71	0.86
5	High Flow	4.3	4.3	0.7	0.7	300	0.08	1.11	1.91	0.31	0.49

Note: Optimizer module within the Controller identified additional scenario where the nitrate recycle to the anoxic cells can be shut off and the glycerol feed can be increased to 400 LPD. This would result in higher cost.

Al Ansab, Muscat, Oman

The configuration and results for N removal at a flat sheet Kubota MBR plant in Muscat, Oman, are shown in Figures 5 and 6. Energy management is of significant importance in MBRs, especially at high MLSS temperatures of 20 to 35 °C. In this analysis, the MLSS management and changes in the operating DO in the activated sludge basin helped increase the alpha values and increase denitrification. By combining analysis with Scenario Manager and Real Time Optimization that changed the operating MLSS and the number of activated sludge tanks, this plant showed the potential to reduce energy more than \$100,000 per year at 50,000 m^3/d (13 MGD) flow (Figure 4) and extend the life of its membranes by 10%. The wastewater strengths are equivalent to a 20 MGD plant in the US.

Figure 5. Layout of 50,000 m^3/d Flat Sheet MBR, Muscat Oman

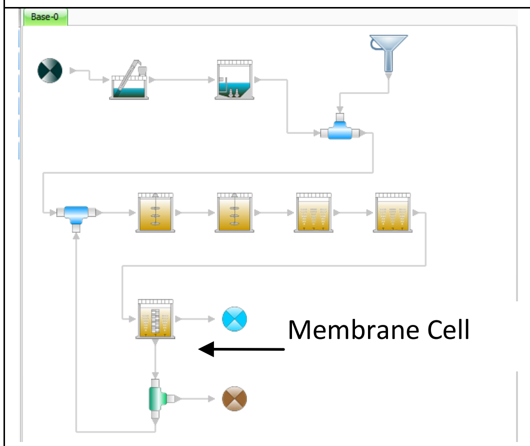
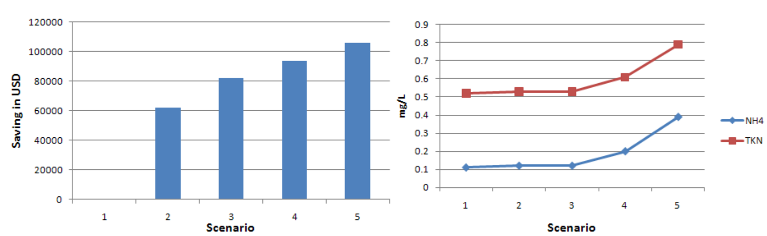


Figure 6. Simulation for Simultaneous Effluent, GHG and Energy Optimization, Muscat, Oman

Scenario	MCRT days	N2O kg/d	NO kg/d	Power KW	Savings USD/year		NH4N mg/L	TKN mg/L	NOxN mg/L	TN mg/L	TP mg/L
1	30	7.51	7.6	457		High Power + GHG	0.11	0.52	4.19	4.71	0.79
2	30	6.35	6.75	356	61933.2		0.12	0.53	4	4.53	0.78
3	30	6.38	6.97	323	82168.8		0.12	0.53	2.93	3.46	0.79
4	**15**	**6.55**	**6.99**	**304**	93819.6	Best Combination	0.2	0.61	3.34	3.95	0.75
5	9	6.94	7.09	284	106083.6	GHG, NH4N increases	0.39	0.79	3.08	3.87	0.71



The anoxic and aerobic activated sludge basins upstream of membrane cell are also operated for flow and load equalization by varying the liquid level in these tanks. The flow is pumped out of the aerobic cell to the membrane cell. In real time mode, the software can be used to advise how to change the pumping rate to extend life and capacity of the membranes by an additional 10%, and reduce energy.

Westminster, Maryland

The example shown here for the Westminster WWTP operating at 5.2 MGD (21,000 m^3/d) is for minimizing the electricity bill at a plant where the power rates change at different times of the day. This is achieved while maintaining the same effluent quality for total nitrogen and phosphorus in a BEPR and BNR system over a 24 hour period. In this instance, the operator uses the Scenario Manager to test out various operating DOs over a 24 hour period and evaluate the corresponding effluent ammonium-N (Figures 7 and 8), nitrate-N and ortho-P. This analysis helps determine effluent ammonium-N thresholds that can be set up in the Artificial Intelligence Routine of the Optimizer for each 15 minute period over a 24 hour period, both for normal and high flows. The Optimizer then manages the operating variables across the entire plant, including the dewatering and operating MLSS to minimize the operating cost and achieve these setpoints.

At any time, the Scenario Manager can be started as a parallel solver while the plant is operating with Real Time Optimization. At Westminster, the operator can initiate the Scenario Manager to also analyze additional septage flows that can be processed on a day when the plant is experiencing high wet weather flows. The plant receives higher than typical flows during wet weather because the old part of the City of Westminster has combined sewers. During the wet weather, the flows can increase from 5 MGD to more than 10 MGD. At flows exceeding 7 MGD, the plant switches partially to a contact stabilization mode. It sends the flows above 7 MGD to the last third of the aerobic zone. As a result, the effluent ammonium-N begins to increase.

To analyze whether the plant can handle septage over the next 24 hours, the operator can run the simulator in an Offline mode (Table 2) with the expected level of flows and different levels of septage. Based on this, the operator can make a decision whether to continue to receive trucks that bring septage or turn them back. The Offline analysis can be initiated at any time in a parallel solver.

For Real Time Optimization, the following approach has been developed for Westminster.

1. The operator can use the Scenario Manager to make a determination what level of ammonium-N is acceptable, and where there may be a sudden and significant increase in effluent total nitrogen.

2. The operator also uses the Scenario Manager to determine DO levels required at different flows. It is used to determine DO level above which it does not make economic sense to operate because of limited increase in the nitrification.

3. Based on knowledge gathered from the Scenario Manager, the AI routine in the Optimizer is set up to operate to different ammonium-N thresholds at different flow rates. Once the threshold is exceeded, the Optimizer changes other operating parameters such as the operating DO. Once the operating DO exceeds a certain setpoint which is also specified in the AI routine based on information gathered from the Scenario manager, the Optimizer asks the operator to reduce the septage feed rates or reduce the wasting rate.

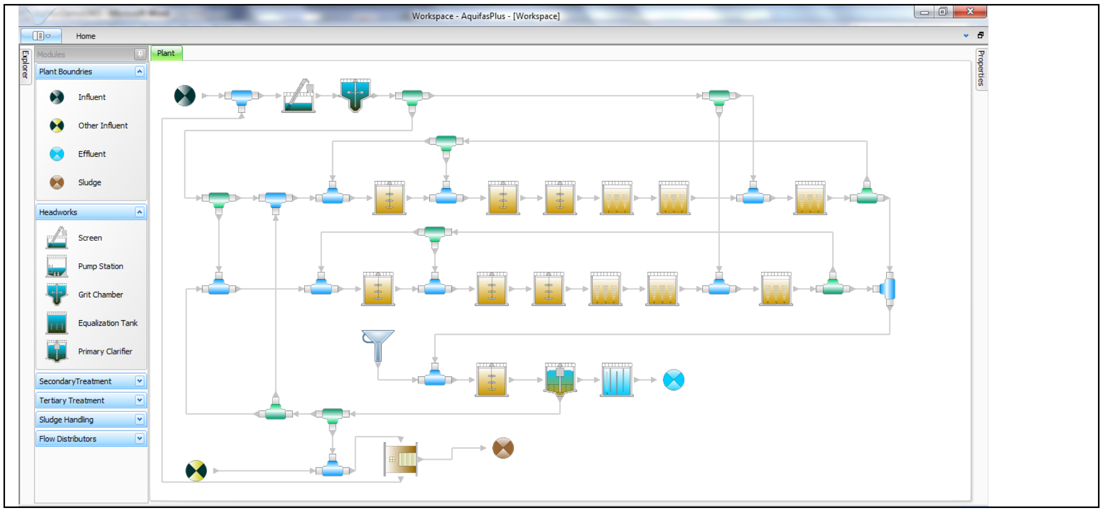
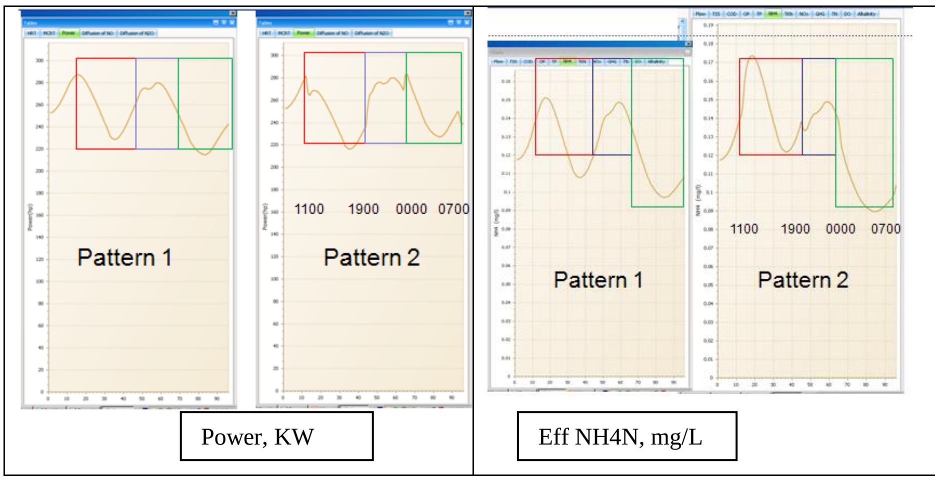


Figure 7. Complete Layout as used in Westminster, MD. The North and South Trains have different types of diffusers.



The aeration pattern is changed by modifying the DO setpoints over a 24 hour period. In this analysis with the Scenario Manager, the DO setpoint was reduced by 0.2 mg/L from 2.5 to 2.3 mg/L during the peak tariff hours and increased after midnight to 6 am during the low tariff hours. This manages the effluent NH_4N and TN at about the same level while reducing electricity costs for aeration by 10%. The operator conducts this analysis in the Scenario Manager following which he reverts to the Real Time Optimizer and uses this information to set up the thresholds of DO (and recycles, etc).

Figure 8. Optimizing performance through Scenario manager to achieve same levels of nutrient removal at lower costs

Lower Lackawanna Valley Sanitary Authority (LLVSA), Duryea, Pennsylvania

At the LLVSA plant (6.0 MGD, 22,710 m^3/d), a fixed media IFAS system will use Bioweb™ media in a Webitat™ module configuration. The Bioweb media is to be installed in each of six parallel tanks. The layout of each tank is with 14 Webitat modules in the aerobic zone, installed in a 7 (longitudinal) x 2 (parallel) mode along the length of the aerobic zone.

The aerobic zone has a dual aeration system with coarse and fine bubble diffusers:

1. The coarse bubble diffusers are attached to the Webitat modules. They are used both for oxygen supply and for air scour to control biofilm. They generate a rapid circulation pattern through the biofilm module to reduce the thickness of the stagnant liquid layer and improve kinetics of nitrification and denitrification in the biofilm. Also, by controlling the thickness of the biofilm, it can help control the nematodes in the biofilm. Air flow to individual banks of modules can be totally turned off independently from the main fine bubble aeration to allow positive nematode (redworm) control through oxygen deprivation.

2. Fine bubble diffusers are distributed across the floor of the tank to provide bulk of the process oxygen demand.

Unlike traditional media systems, the simulator is being enhanced to compute the effect of recirculation through the Webitat modules. It is also being upgraded to simulate a dual aeration diffuser system, where the depth and type of diffusers are different.

The simulator is being applied for real time control of the IFAS process. It will provide feedback to the operator to help select the best operating conditions for normal and high flows. Further, the conditions included in the artificial intelligence routines are being upgraded to help the operator maintain the correct operating conditions in the biofilm, such as:

1. Maintain the specified levels of organic carbon and ammonium-N at different modules along the length of the tank. This is achieved by controlling the MLSS levels appropriately in summer and winter. This helps prevent periods of operation when the biofilm is starved of organics. At some plants, this leads to an increase in nematodes. One should note that nematodes can establish on fixed bed and moving bed media and need to be controlled by the air scour and the operating conditions. The dashboard of the simulator displays the soluble BOD_5, soluble organic COD, ammonium-N, nitrite-N and nitrate-N upstream of each fixed bed module in the aeration tank (Figure 2a).

2. Maintain desired organic carbon levels in the first few biofilm modules along the aeration tank to improve denitrification achieved in the aerobic zone, thereby optimizing denitrification in IFAS fixed bed. Using this approach, it may be possible to achieve up to 50% denitrification in the aerobic zone of the fixed bed IFAS system, as compared to 20% typical for moving bed systems.

3. Control the operating DO with fine bubble aeration in different zones, while maintaining the hydrodynamics and air scour with the coarse bubble diffusers. The operating DO is managed to maximize the nitrification and denitrification within the aerobic zone while achieving thresholds for effluent ammonium-N. This will help manage and minimize the supplemental carbon requirement to the post anoxic zone.

Other plants (35 to 200 MGD)

Earlier versions of the simulator have been applied at Polebridge and Snapfinger MBR plant upgrades (45 to 70 MGD) outside Atlanta, Georgia. The Syracuse Metro plant, NY (90 MGD, high rate activated sludge followed by nitrification filter) and Backriver WWTP, MD (200 MGD) for BNR upgrade used some of the components. The asset management model has been evaluated using information from several water treatment plants with capacity up to 100 MGD, and at Utilities managing more than 250 MGD of production.

Integration with PLCs and Sensors, Nestle (equivalent to 5 MGD municipal)

The simulator is also being integrated with I/O ports of Allen Bradley PLCs, with Endress Hauser transmitters and with data structure to link to DCS systems as part of a complete hardware and software package. The hardware-software package adds a few sensors at key locations along the plant to help with the optimization. Data from flows and from these sensors provide forward feedback to the model to drive the dynamic simulation. Additionally, a sensor is added on the effluent to check the effluent data predicted by the model or use laboratory data when that is not feasible. The simulator has an internal tool to check its calibration at each time step before running the optimization routines.

DISCUSSION

One of the requirements for developing such a system is its applicability to plants from 0.25 MGD to 250 MGD; and to municipal and industrial plants. The following discussion addresses the challenges and opportunities at different sizes and types of plants. It discusses unique initiatives such as the development and maintenance of chemicals database specific to ENR plants and their needs; and use of algorithms to manage the periodic inhibition experienced with septage treatment at ENR plants.

Addressing Challenges at Small Plants

There are considerable challenges in applying the system to small plants (flows less than 2 MGD). There is a current initiative in Maryland in collaboration with Maryland Center for Environmental Training (MCET) to allow the small plant operator to send data to the simulator using Excel and retrieve the results using Excel.

While the software may be installed as a troubleshooting tool at the small plant, a server based installation may work better for a Utility that has to manage several small plants with limited staffing. A method of extracting and exchanging data once a day as data packets and running the system for each plant on the server is being evaluated. This is equivalent to the method used in the Offline mode, which runs 96 time steps once a day.

Addressing Opportunities at Large Plants with Anaerobic Digesters

Large plants represent unique opportunities to apply Real Time Optimization of assets, increase energy production in anaerobic digesters and reduce the energy requirements in secondary treatment systems. Over time, there is the potential to change the operating mode at large plants such that they can enhance their energy production by 10 to 20% and reduce the aeration energy requirements by 10 to 20%. Ultimately, the optimization and control logic may allow many more plants to become net generators of energy while satisfying fairly stringent nutrient removal permits.

One of the enhancements being made at this time is to implement real time adjustments to operating capacity and maintenance of primary treatment systems; next year, this will be upgraded to include chemically enhanced primary treatment. The chemically enhanced primary treatment can be turned on and off by the plant. It can be turned on during high flows.

The integration of asset management with whole plant and digester economics (Sen *et al*., 2012) can allow each plant to discover means to increase the organic carbon load to the digester by 10% and increase the energy production where cogeneration is practiced. Table 5 shows an example:

Table 5. Optimization of Plant with Anaerobic Digestion
This is a "static" example to represent a typical normal flow. Actual plant optimization will be time dynamic.

	Without Primary Clarifier Optimization	With Primary Clarifier Optimization
Raw Influent COD, mg/L	400	400
Primary Effluent COD, mg/L	280	250
COD shunted to digester	120	150
Digester Gas Production, relative units	1	1.1
Centrate TKN, mg/L	300	330
Primary Effluent TKN, mg/L	30	32
COD/TKN ratio, primary	9.3	7.8
Aeration Energy, relative units	1	0.92
Effluent NOxN, mg/L	4	3.9
Operating DO, mg/L, 15 C	2.0	1.6
Digester Sludge production, relative units	1.0	1.02

Savings in aeration energy = $100,000 per year at 25 MGD (100,000 m^3/d)
Additional electrical energy generation = $30,000 per year at 25 MGD
Assumption: Rates paid by Utility for energy generation are half the rates charged by Utility
Additional chemicals for enhanced Primary clarification = $10,000 per year at 25 MGD
Net savings = $120,000 per year at 25 MGD (100,000 m^3/d)
Operational cost savings over 20 years from real time optimization of operations = $2.4 Million

Based on experiences with real time asset and redundancy management, an equivalent amount of savings can be generated over a 20 year period from real time asset management. However, these savings are weighted more heavily in the second half as and when infrastructure replacement costs come into play. The AMIDST tool is used to help extend life of infrastructure and find ways to improve financial efficiency of infrastructure investments (Sen et al, 2012).

By using the optimizer, it is possible to manage the effluent from secondary treatment system such that the effluent NOxN is lower despite the additional carbon shunt shown in Table 5. This is because of the reduction in organic carbon load in the primary effluent reduces the biomass production in the secondary treatment system. This can allow for operation at a higher MLSS MCRT and lower DO setpoint. One should note that in some instances, there will be a marginal increase in soluble refractory total nitrogen (estimated to be less than 0.05 mg/L) as a result of shunting more nitrogen to the digester. One would set up the the operator to maintain better conditions to manage the foam and the SVI. SVI and foam are treated as attributes of assets around which thresholds can be specified in the Artificial Intelligence routine.

The increase in carbon load to the digester increases the nitrogen load. This results in an increase in the nitrogen recycled by 10%. For digesters that operate only on certain days of the week, it becomes especially important to manage the increase in nitrogen recycles in the secondary treatment system. Through optimization, one can reduce the energy requirements from 8 to 15%. On days when the plant experiences significantly lower MLSS temperature, as when excess wet weather flow stored in a detention basin is sent to the system in winter, the optimizer would respond by changing the DO setpoints to compensate for the temperature. The nitrates would increase slightly for those days but overall, on an annual basis, the total nitrogen could be lower.

Table 5 shows the one of the aspects of global optimization wherein the plant can not only maintain its effluent quality under the variations in flows and temperatures, but also can reduce the energy requirements for aeration and increase the digester gas production.

What is generally not recognized in large plants is that a significant amount of savings can also be generated by optimizing the utilization of assets such that they last 10 to 20 percent longer. This can be implemented by reducing the demand on blowers, pumps and mixers; it is also done by special asset analysis and management tools (AMIDST) discussed by Sen *et al*. (2012) which enable an asset management and technical support team to conduct a more in-depth analysis to find optimum solutions and investments.

Extending the System with Live Link to a Database of Chemicals for ENR plants

One of the features being incorporated as part of the current initiative funded by Maryland Center for Environmental Training is to create a special database of chemical types with attributes that are important for ENR plant operations and for design. The information in the chemicals database is important information when a plant or process engineer considers switching from one SKU (Stock Keeping Unit) of a chemical to another from the same vendor, or considers switching to another vendor, or switching between chemicals. Such a database is geared to the Mid-Atlantic States. The problem with chemicals is best explained with experiences with Poly Aluminum Chloride (PACl) used for chemical P removal at ENR plants in the Mid-Atlantic states. At this time, Delta Chemical provides PACl with four basicities; General Chemical provides PACl with five other basicities, InterPAC provides other basicities (eg: InterPAC 113 has a basicity of 35 +/-5%, Delta Chemical has basicity ranges from 30 to 70 percent). A typical MSDS, as received by InterPAC is shown in Table 6. It is generally correct but has some inconsistencies with other manufacturers. This poses considerable challenge at the operations level when operations staff has to understand the subtle differences between these chemicals when they want to consider various options available to them; when manufacturer's representative sends in the wrong information as has happened more than once and the operator does not have sufficient knowledge to correct the information. In the case of PACl, the basicity of PACl is important, especially at plants that otherwise need to add more alkalinity. However, it needs to be checked against the aluminum content. Unfortunately, basicity is a term that is hardly discussed in text books and taught to design engineers.

The upgrades being made to the simulator in 2012-13 will allow one to link to a chemicals database, where the relevant attributes of each SKU are geared to a water, wastewater and water reuse plant operating for nutrient removal. The structure is being put in place to continually add to the knowledge contained in this database for use in operations and optimization. The chemicals database is being developed with the attributes relevant to ENR and maintained/updated in conjunction with MCET.

Management of Septage and Leachate at BNR and ENR Plants

An additional initiative in the Mid-Atlantic region is to incorporate the behavior and response to certain chemicals that are present in boat waste, septage and leachate in the activated sludge and biofilm models. Since chemicals such as formaldehyde are not measured directly in the septage, the plant does not have a "readout" of inhibitor concentration in the septage. Instead, the algorithms in the simulator are being refined to analyze the difference in the computed values of ammonium-N and ortho-P from the optimization and the sensors at various points along an activated sludge basin and in near real time. This is then used to warn the operator if there is a potential for disturbance in biochemical processes as a result of the current batch of septage, boat waste or leachate. When this happens, the Optimizer will advise the operator how much to reduce the pumping rate of septage. This recommendation is adjusted by the optimizer for normal and high flow conditions.

The operator can also override the recommendation and decide to process more septage. The operator can then use the Scenario manager to analyze how best to adjust the operating setpoints in the rest of the plant to process the higher quantity of septage or leachate. This is done by switching to a different set of operating conditions and thresholds in the Artificial Intelligence routine. These conditions tell the software that the plant is required to process a higher septage. The Optimizer will recommend in real time how best to operate the plant to process the higher flow rate of septage.

As part of an initiative funded with MCET, inhibitors were simulated in the Mid-Atlantic region. They are being added to the ASM2d Model. The installation of the Optimizer will be able to sense the presence of the inhibitor in a particular batch of septage, boat waste or leachate and respond accordingly.

Additional Analytical Features for Asset Management Teams

Work is underway on the asset management model to capture the information from optimization routines to determine better values of Consequence of Failure (COF) for each piece of equipment in the plant that influences the operating condition (Sen et al., 2012). Typically, COF values are conducted in a Delphi type of workshop, where staff who have some previous experience on the response of the plant to the failure of a particular asset help share this experience. Based on these anecdotes, the asset management team makes the most educated guess of values that are aggregated to compute the COF. The COF is then used to compute the Business Risk Exposure (BRE), where BRE = POF x COF. To help quantify this more accurately, tools are being developed to periodically conduct 10,000+ combinations of setpoints of operating conditions and equipment availability at the plant, together with the collection system and in the water reuse distribution network. These simulations help show the response of the plant to failure of the asset, and to combinations of assets. This is then used through a statistical analysis to derive values of components of COF. These are discussed in Sen *et al*., 2012. Based on this information, one is able to refine the value of COF developed in a Delphi workshop, or provide more data to attendees in a Delphi workshop. The asset management team running the simulator can analyze many additional combinations which are otherwise not possible in the amount of time available. Having a better graph of the COF helps the team optimize the investment decisions for capital projects and help the Utility and the plant make the right investment at the right point in time.

A second feature of the tool is to help the asset management team identify more opportunities to identify projects which will increase the financial efficiency of operations. It does this by identifying what is termed in the industry as financial efficiency failure, not just around one set of pumps but around combinations of systems. This data can then be used by the asset management teams to make the right investment decisions with the right scope and at the right time.

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