Use of Modeling for Optimization of Activated Sludge Process Design

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Simulation software has been used for the design and optimization of wastewater treatment plants for several decades, with different program packages commercially available. The activated sludge modeling underlying the commercial programs is primarily based on the open-source research on activated sludge and other treatment processes published in the literature. While simulators cannot replace engineering judgement in all aspects of designing a water resource recovery facility (WRRF), they provide a useful tool in efficient evaluation of various treatment options and operational scenarios.

Following a brief outline of some basic features of the commercial simulators, this article discusses several case studies from real-life design practice. In these case studies the commercial software was used to aid in some basic tasks in a process of WRRF design, primarily using steady-state modeling.

Features of Commercial Simulators

The initial thrust of the simulators was to model steady-state and dynamic behavior of an activated sludge process, particularly in respect to nitrification, denitrification, and phosphorus removal. Modern commercial software packages include an ever-increasing range of various treatment units found at WRRFs that can be represented or modeled. These include the following:

- A range of activated sludge bioreactors: suspended growth (diffused air or surface aeration), various sequencing batch reactors (SBRs), media reactors for integrated fixed-film activates sludge (IFAS) and moving bed biofilm reactor (MBBR) systems, trickling filters, and variable volume reactors.
- Anaerobic and aerobic digesters.
- Various settling tank modules, from simple "point clarifiers" to those capable of modeling clarifier performance.
- Different wastewater and chemical input elements: wastewater influent that is chemical oxygen demand (COD)- or biochemical oxygen demand (BOD)-based, metal addition for chemical phosphorus precipitation, and carbon source.
- Other process units: holding tanks, equalization tanks, grit tanks, filtration/microscreen, and dewatering units.
- Novel treatment units, such as aerated filters, thermal hydrolysis units, and sidestream-treatment deammonification processes.

The simplest form of modeling uses the steady-state approach, where wastewater flow and characteristics remain constant. For more sophisticated, dynamic modeling, simulators provide the ability to program variable flow and wastewater strength pattern, among other factors. The commercial packages come with a user-friendly interface offering output that could be presented in various tabular and graphical forms, including broadcasting of "live" dynamic modeling and much more.

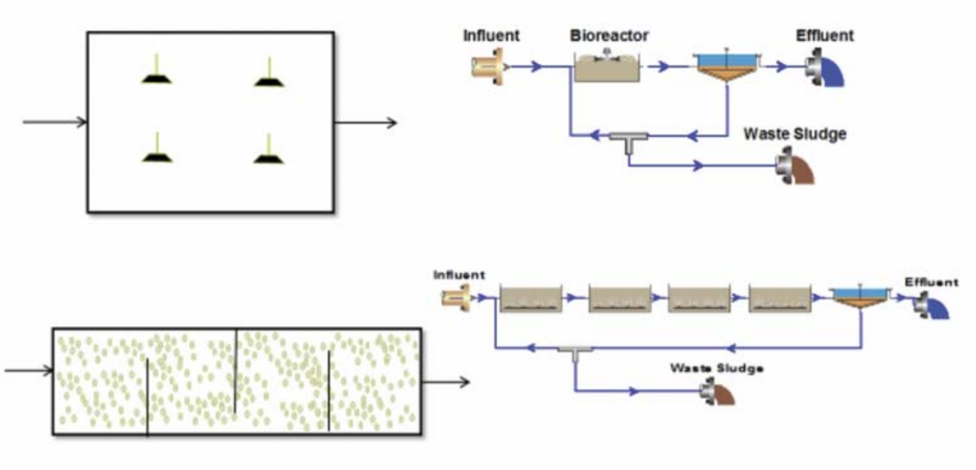

Figure 1. Representation of completely mixed versus plug flow (multiple tanks in series) flow regime.

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Calibration

As with any computer program, the reliability of the outcome will be heavily dependent on the assumptions and inputs provided. While models come with a full set of default kinetic and stoichiometric parameters, calibration procedures are highly recommended. During the calibration process, the model's physical setup, solids mass balance, and consistency with actual performance (in a brownfield application) should be verified and tested. Depending on the available data and resources, the following levels of calibration could be accomplished:

- *Level 1- Defaults and assumptions only*. Better than textbook design guidelines, this level could be used for comparative analysis of alternative configurations for biological nutrient removal (BNR), particularly in greenfield application.
- *Level 2 - Historical data only*. Data from a period of stable operations should be used for calibration. Closing of solids mass balance could be particularly challenging if solids wasting and other data are not accurate. Include impact of sidestreams, estimating if needed. Availability of primary clarifier effluent quality data is important (if the case). Very useful for calibration is the availability of data from process upset, such as nitrification failure at low temperature.
- *Levels 3 and 4 - Special testing.* These levels require collection of additional data and site-specific testing for supplemental wastewater characteristics and influent fractionation data, and data from intermediate treatment points and recycle streams.

The references noted at the end of this article provide comprehensive information on all aspects of modeling, including dynamic simulations and procedures for detailed calibration. Developers of commercial software packages have various training offerings, which could be highly useful in developing modeling proficiency.

Case Studies

Simple examples from real-life projects are provided, illustrating how simulation software could be used to aid in several aspects of activated sludge design. These include the following:

1. Realistic representation of mixing and flow regime for nitrification
2. Modeling of oxidation ditch performance
3. Optimization of diffuser distribution for a swing zone
4. Use of dynamic modeling for determination of diurnal oxygen demand variations
5. Accommodation of variable dissolved oxygen (DO) set points
6. Design of pre-anoxic zone without internal recycle

Realistic Representation of Mixing and Flow Regime Nitrification

A realistic representation of the mixing regime and flow profile in the aeration basin could be important for proper modeling of the processes, such as nitrification and oxygen demand distribution. When a single, completely mixed tank or a series of tanks with well-defined segmentation (baffles) are present, the representation by the model is straightforward (Figure 1).

When tanks with a high length-to-width ratio are present, a more realistic representation is a conceptual division of the long tank into two or more smaller, completely mixed tanks (zones). Further refinement could be achieved by introducing back-mixing between such conceptual zones, with a back-mixing stream flow rate set at one to five times the forward flow as a first approximation (Figure 2). A more rigorous mixed liquor flow profile could be established based on a tracer study or computation fluid dynamics (CFD) modeling, but this would be practical only for larger facilities/projects.

As mentioned, a proper hydraulic representation of the aeration tankage in modeling is important for a realistic performance of the activated sludge system, particularly in terms of nitrification. Nitrification kinetics, being nonzero order, is affected by flow and mixing regime. Table 1 illustrates the effect of different hydraulic/mixing representation of the same aerated volume on the effluent ammonia under steady-state conditions.

Modeling of Oxidation Ditch Performance

An oxidation ditch represents a special case of aeration tankage configuration, which may not be directly represented in a commercial software package. The unique feature of the racetrack basin from the standpoint of modeling is a high degree of internal recirculation with a single (typically) point of oxygen input and the resulting gradient of oxygen concentration. Figure 3 provides an example of simulator representation of

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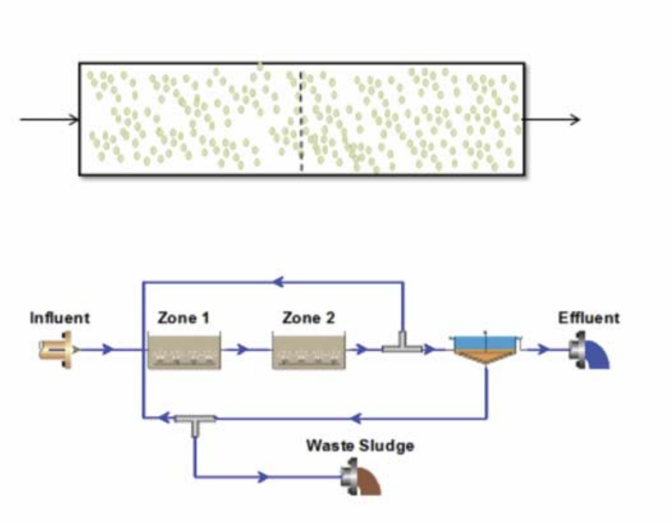

Figure 2. Realistic representation of mixing regime in a rectangular tank with large length-to-width ratio (the baffle shown is "virtual").

Table 1. Effect of mixing/flow regime on effluent ammonia.

Flow Regime	Effluent Ammonia, mg/L
One completely mixed tank	1.37
Plug flow (four completely mixed tanks in series)	0.19
Two completely mixed tanks in series, no back-mixing	0.57
Two completely mixed tanks in series with 5 x Q back-mixing	0.87

NOTE: All conditions, including total aerated volume, are the same in all cases (HRT = 6 hrs, temp = 20 °C, MLSS = 2,600 mg/L, BOD_5 = 245 mg/L, TKN = 45 mg/L).

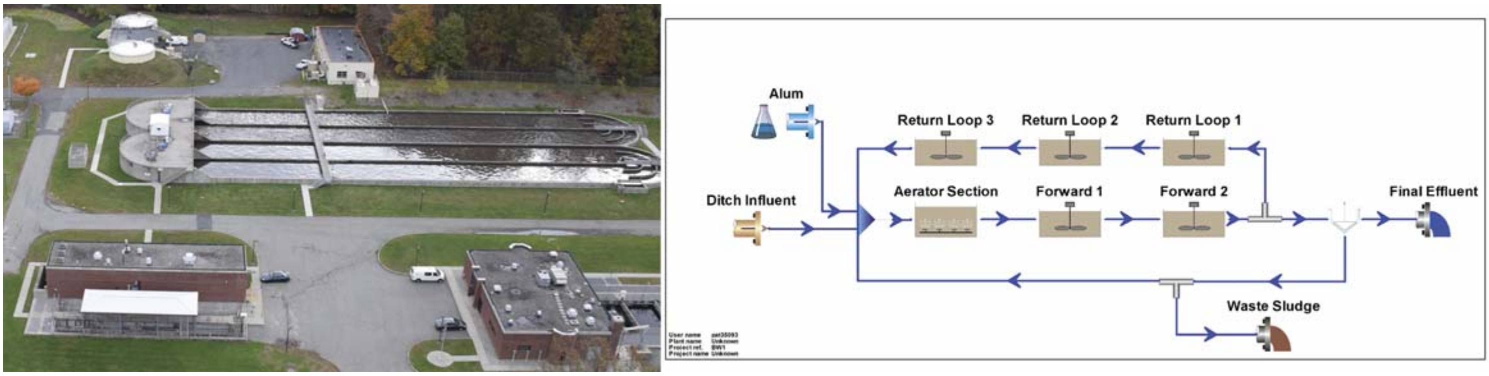

Figure 3. Oxidation ditch configuration for modeling.

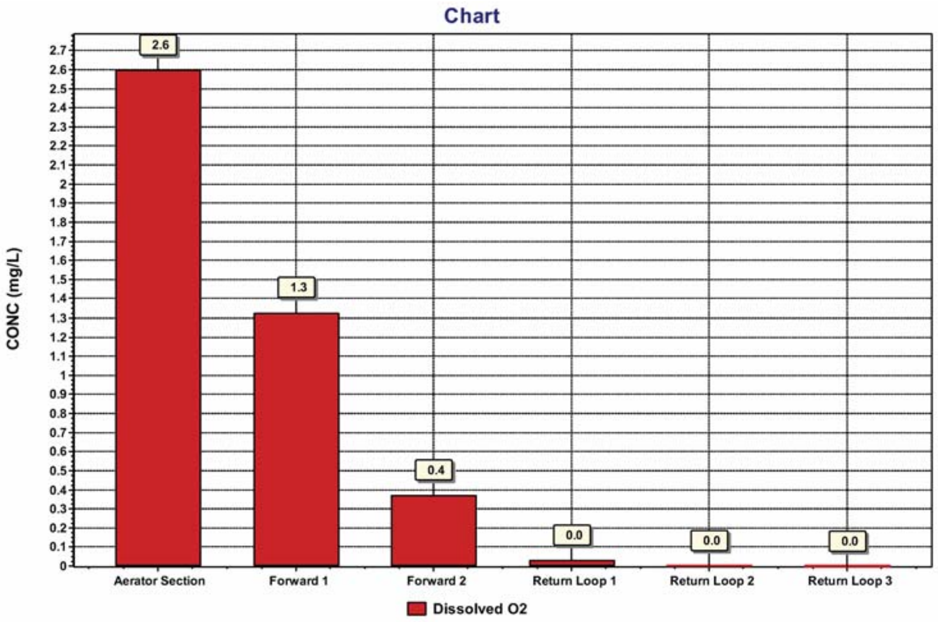

Figure 4. Oxygen profile along the oxidation ditch sections as represented in Figure 3.

Table 2. Simulation of oxidation ditch performance at future flows.

Parameter/Case	Monthly Avg. Limit	Simulated Performance at		
		1.832 mgd	2.5 mgd	3.1 mgd
NH3-N, winter (8 °C), mg/L	3.9	1.62	1.95	2.56
NO3-N, winter (8 °C), mg/L	10	4.25	5.44	5
NH3-N, summer (23 °C), mg/L	1.4	0.34	0.34	0.36
NO3-N, summer (23 °C), mg/L	10	3.3	3.7	4.05

Table 3. Diffuser distribution design of a swing zone.

1	2	3	4	5	6	7	8	9	10
	12 °C (Cell C2 On)			Compromise Diffuser (AOR) Distribution				12 °C (Cell C2 Off)	
MLSS mg/L	2,942			Max. AOR capacity, kg/d			Actual operating AOR with C2 aerating	3,439	
	% of train air	AOR, kg/d	% of train air		% of train air	% of train air		% of train air	AOR, kg/d
	Base		If C2 Off		C2 On	C2 Off	C2 On	Base	
C1 (anoxic)									
C2 (swing)	27%	6,076		8,500	27%		6,177		
C3 (aerobic)	30%	6,612	41%	9,961	32%	44%	7,239	45%	9,961
C4 (aerobic)	26%	5,729	35%	7,500	24%	33%	5,451	31%	6,940
C5 (aerobic)	18%	3,971	24%	5,146	17%	23%	3,740	23%	5,146
Total	100%	22,388	100%	31,107	100%	100%	22,607	100%	22,048

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a simple oxidation ditch with a single surface aerator.

Subdivision of the ditch volume into several zones allows for a good representation of physical reality, with only one cell being aerated. The ditch recirculation factor is a key characteristic impacting the rate of depletion of oxygen and residual DO in the remaining zones, as calculated by the simulator (Figure 4). An initial assumption regarding the rate of recirculation could be derived from a typical wastewater velocity in the channel of, say, 1 ft/second, and the channel's cross section. This rate could then be compared with a measured DO profile along the ditch to arrive at a realistic internal recirculation rate, which in this case would be 150 times the forward flow rate. A model calibrated in this simple fashion could then be used, for example, to determine the plant's ability to meet ammonia and nitrate limits at future flow conditions. The internal recirculation rate for higher flows should be scaled back to provide a similar wastewater velocity for all flows.

Table 2 provides the results of such simulations, with the lowest flow rate corresponding to the current conditions. The primary variable in striking the right balance between the degree of nitrification and denitrification is oxygen supply (DO set point) at the aerator, as adjusted by the variable frequency drive (VFD) and weir level. This, together with other physical model assumptions, will govern the aerobic versus anoxic conditions along the ditch and dictate the degree of denitrification (Figure 4). The results indicate that the plant should be able to meet the permit limits, even at the full maximum month flow conditions.

Optimization of Diffuser Distribution for a Swing Zone

Oxygen demand varies considerably along the length of an activated sludge tank, regardless of its configuration or the presence of physical dividing walls or baffles. To optimize air utilization and maintain a desired DO set point at all points in the aeration tanks, a tapered aeration system is commonly used. This primarily involves the use of staggered density of the diffusers in different sections of the aeration basin, with "virtual" baffles used, as discussed in the first case study. In the absence of adequate distribution of the diffusers, the operation of the system at the desired residual DO may depend on throttling air flow to various headers, which will result in increased pressure and inefficiencies.

Simulation software could readily calculate the oxygen uptake rate in various sections of the aeration basin. In most cases this could be straightforwardly translated into a diffuser density, with the total amount of diffusers and air demand calculated through well-established "manual" procedures or with the use of special aeration system design features available in some programs.

A special case of diffuser distribution design is present when a swing zone is incorporated into the treatment train. As the mode of operation of the swing zone impacts air demand distribution between the various zones, a distribution that is an acceptable compromise for both cases is needed. If an acceptable compromise is not possible, the alternative is an interlaced air grid design with the ability to isolate part of the diffusers in various zones, as needed, for the particular mode of operation.

Table 3 illustrates a compromise design of the diffuser distribution for an expansion of a 33-mil-gal-per-day (mgd) facility with a year-round nitrification requirement. Zone C1 is a dedicated anoxic zone, C2 is a swing zone, and zones C3 through C5 are aerobic. (Note that zones C1 and C2 are smaller than the remaining, dedicated aerobic zones in this example.) Column 3 provides actual oxygen requirement (AOR) calculated by a simulator software for each zone in the case of zone C2 aerating. Column 2 shows the relative air requirement distribution (equal to the relative number of diffusers) for this case. If air to zone C2 was switched off for such diffuser distribution, the relative air distribution among the remaining three aerobic zones will be as indicated in column 4. Columns 9 and 10 show the simulator-calculated AOR distribution for the case of C2 operating as an anoxic zone. Comparison of columns 4 and 9 indicates that the optimal distributions for the two cases are not far apart and that a compromise distribution could be constructed. This is shown in column 5, with the resulting diffuser distribution being a good compromise between both operating modes of zone C2. (Compare column 2 with column 6 and column 9 with column 7.)

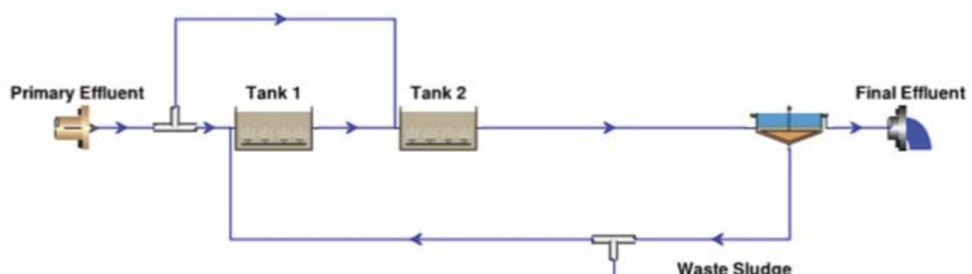

Figure 5. Flow schematics at a 28-mgd plant with step-feed configuration.

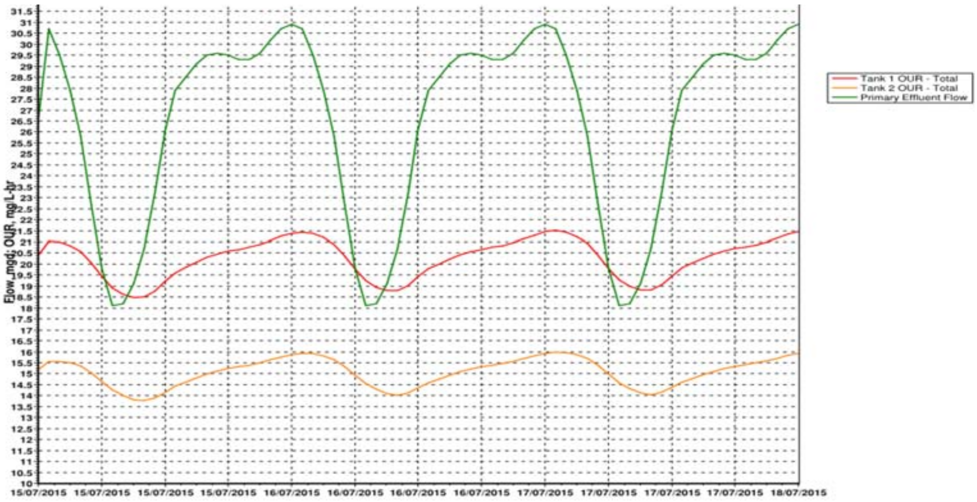

Figure 6. Output of dynamic simulation of diurnal oxygen demand profile.

Table 4. Summary of flow and oxygen demand peaking factors.

	Maximum Daily to Average Peaking Factor	Minimum Daily to Average Peaking Factor
Flow	1.18	0.61
Oxygen Demand	1.08	0.92

Use of Dynamic Modeling for Determining Diurnal Oxygen Demand Variations

Diurnal flow and load variations impact oxygen demand throughout the day; however, oxygen demand is not directly proportional to the influent load. The equalization effect of the large aeration basin(s) and the distribution of residual carbonaceous biochemical oxygen demand (CBOD) and ammonia in the tankage all impact the degree of oxygen demand variations. Simulation software could facilitate understanding of these variations to arrive at a realistic peak oxygen demand during an average day.

Figure 5 provides a flow schematic of a 28-mgd plant with two tanks in series and a step-feed configuration. The plant was undergoing an upgrade of the aeration system, including new blowers. Determination of a realistic, sustained daily maximum oxygen demand under typical conditions was an important factor in sizing new blowers. Lacking data on influent concentration variability during the day, the flow was used as a surrogate for load variations. A typical dry weather diurnal flow pattern was developed from plant influent data and the flow schedule was programmed into the simulation software.

Figure 6 provides the results of dynamic simulation of the oxygen demand variability through a typical day in both aeration tanks. As evident in Figure 6, oxygen demand profiles in both tanks (orange and red lines) were much flatter than flow (load) variations (green lane). Based on these results, the profile of a combined oxygen demand from both aeration tanks was determined. Table 4 contrasts the resulting diurnal peaking factors for the oxygen demand with the corresponding flow peaking factors. This information allowed for a more confident selection of the duty blowers to service the plant during normal operating conditions.

Accommodation of Variable Dissolved Oxygen Set Points

While the residual DO is typically targeted to be equal in all points of an aeration basin (usu-

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ally at 2 +/- 0.5 mg/L level), some cases may call for a structured residual DO design. This may include the following cases:

- Higher DO set point in the first aerated section in an enhanced biological phosphorus removal system, as there is some evidence that an ample supply of oxygen immediately after the anaerobic/anoxic zone improves phosphorus removal.
- Lower set point in an aeration basin section from which an internal recycle (IR) stream for denitrification is withdrawn.
- Lower set point in an aeration basin section immediately preceding a postanoxic zone.
- Lower set point in the last section before the final clarifier to prevent overaeration/bubble entrapment in the mixed liquor entering the clarifier; or conversely, when in some cases a higher set point may be desired to minimize denitrification in the clarifier.

The DO set point preference can be readily incorporated into simulation software, which will calculate air flow required for a specified condition of the oxygen transfer process. Alternatively, relative values of AOR/standard oxygen requirements (SOR) ratio for different zones could be calculated based on the temperature and the residual DO and translated into diffuser density design.

Design of Pre-Anoxic Zone Without Internal Recycle

One of the common activated sludge BNR configurations is the pre-anoxic zone with IR, which allows for utilization of organic carbon in raw wastewater to achieve a significant degree of denitrification. In cases where denitrification is not required by permit conditions, and IR is not desired or practical (owner's reluctance to install and maintain large-flow IR pumps, constructability), incorporation of the pre-anoxic zone without IR may be an inexpensive and practical means of achieving partial alkalinity recovery and lowering oxygen demand. Use of simulation software allows for an efficient demonstration of the benefits of a pre-anoxic zone and optimization of its size.

Summary

Modern simulation software facilitates an efficient assessment of the impact on performance of factors such as recirculation rate, size of reactor, DO set point, temperature, etc. A graphical interface allows for an illustrative representation of the process flow schematics; however, not all aspects of plant design could be reliably modeled, including factors such as sludge settling properties (i.e., acceptable mixed liquor suspended solids [MLSS] levels) or the impact of factors such as the presence of inhibiting constituents.

References

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