A STEP FORWARD IN THE SIMULATION OF DIFFUSED AERATION SYSTEMS

Caroline Crosby, CH2M Beca Ltd
Kevin Brown, CH2M Beca Ltd
Matt Sheehan, CH2M Beca Ltd
Rob Fullerton, CH2M Beca Ltd
Wyllhem Roge, CH2M Beca Ltd

ABSTRACT

A quandary exists between the continuing desire to reduce aeration energy costs at activated sludge plants, and the difficulty of testing and implementing the advanced control strategies and efficiency improvements needed to do so. Biological simulation models are useful in this regard, and are commonly used to outline aeration control strategies. The level of approximation that is necessary in these models means that translation from the simulator to full-scale plant can be difficult. In addition, the models have limitations concerning the physical and control aspects of the aeration system.

As a means of addressing this difficulty, CH2M Beca has developed a real-time interface between GPS-X, a biological simulator, and IDEAS, a process simulator, whereby a simulation of the treatment plant physical aeration system can be integrated with the simulation of the biological processes. Both packages are proprietary and commercially available. The interface has been successfully developed. This paper details the project development and results, from concept through to the first combined-plant model.

KEYWORDS

Wastewater simulation modelling, aeration, diffuser, process, GPS-X, IDEAS

1 INTRODUCTION

Why do wastewater treatment plant staff "sigh when confronted with yet another simulation model optimisation exercise, that demonstrates yet another innovative aeration control methodology"? (Ingildson, 2005) Developments in process control instrumentation and sensors mean that it is now possible to develop complex aeration control algorithms based on a number of important process variables. Ongoing developments in biological simulation modelling mean that interest in these strategies is also increasing, as they can be investigated prior to actual implementation, reducing the process risks involved. Standard biological wastewater simulators are now able to simulate, to varying degrees, advanced dynamic aeration control strategies and have saved treatment facilities a lot of money in many case studies (e.g. Crosby and Fullerton, 2007). The answer to this question lies primarily in the fact that the ability of these biological models to simulate advanced control strategies continues to outstrip the ability of actual control systems and equipment to implement the simulated strategy.

In a biological simulation model, the physical reality of imperfect instrumentation, valve actuation, headlosses and pressure changes in mechanical pipework, and air blower performance are among the variables not taken into account. The ability and efficiency of the physical aeration system to respond to the large and continual disturbances that occur at a treatment plant as a result of the influent dynamics and ambient conditions cannot be easily quantified. The performance of "tuned" model controllers is at best an approximation. Thus major contributors to the performance of the aeration system as a whole are approximated through the use of coefficients and other model calibration parameters.

As shown in Figure 1, an activated sludge aeration system consists of two major subsystems that are not independent, but are only indirectly linked. The primary, or biological, system consists of the plant biomass in bioreactors. The biomass exerts an oxygen demand in response to the influent wastewater characteristics. The major control handles for the biological system include Solids Retention Time (SRT), recycle rates, external carbon dosing, and aeration control. As this is a biological system, there are no totally independent loops, and there is always interaction between control handles. Within this system, optimisation becomes complex and there is usually a tradeoff when improving any aspect. Control variables are selected from within the biological system (most typically the dissolved oxygen) and used to control the secondary aeration system.

The secondary system is the physical aeration system comprising air blowers, air distribution pipework, manual and actuated valves, control hardware and software and aerators or diffusers. The control handles available in this system include the number and position of actuated valves and air blowers, and the way in which these are manipulated. This system acts in response to dynamic disturbances in the primary system. As a result of this response additional dynamic effects in the secondary system are created. For example, temporary pressure changes effect changes in airflow split along pipework to diffusers, which can in turn affect the primary system, and so on. Thus the interaction between the two systems becomes an ongoing series of dynamic interactions in which each system continually elicits a response from the other.

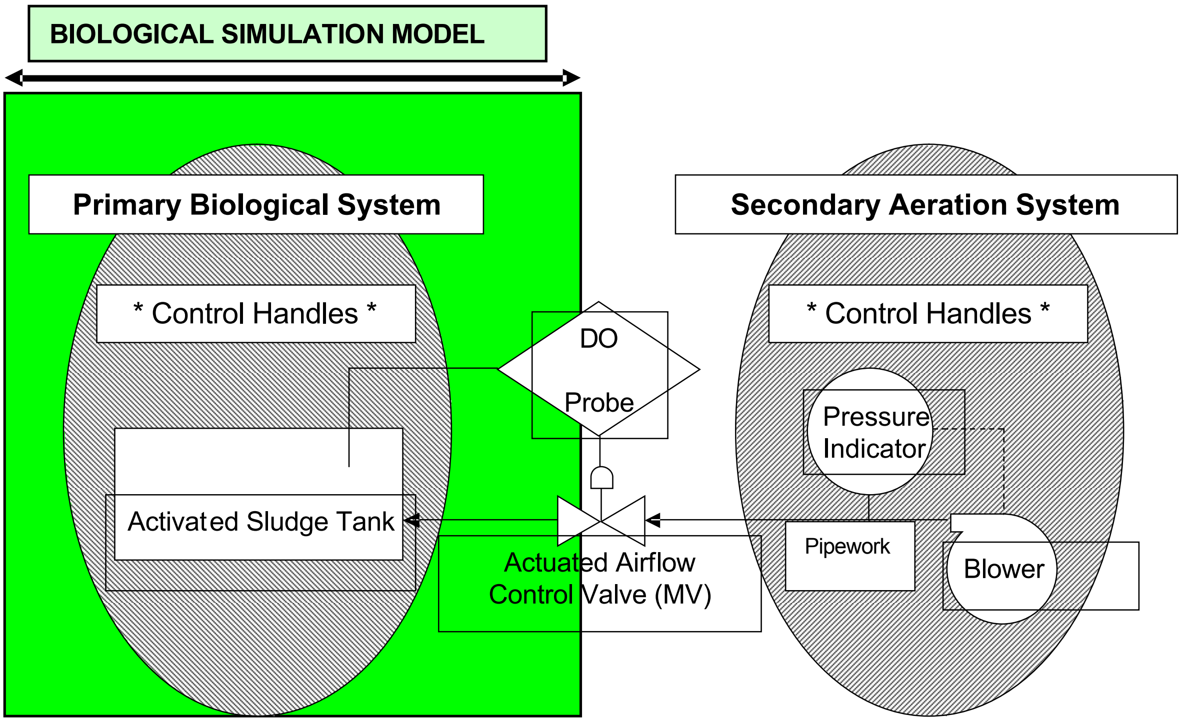

Figure 1: The two subsystems making up an activated sludge aeration system, showing the scope of standard biological simulators

This discontinuity between the simulated biological system and the physical reality of treatment plant systems has to some extent inhibited the development of many advanced full-scale control systems (Ingildson, 2005). Yet the energy use and operational cost associated with aerobic wastewater treatment systems is large. The oxygen requirements of the activated sludge organisms are such that aeration typically accounts for between 40 – 90 % of the total energy use of a facility and accounts for around 15 – 25 % of total operating costs depending on the process used and site specific considerations. This creates a driver to continually improve the efficiency of aeration control, and this can only be done by advancement in aeration control strategies, and improvements in the physical air delivery systems. Many facilities now have reasonable control strategies, and improvements are becoming more difficult to find. Thus there exists a quandary in which advanced aeration control is needed, but in order for it to be implemented at a plant more “proof” of effectiveness is needed than that afforded by a standard biological simulation.

Being able to simulate both subsystems concurrently reduces the approximation involved in the design of aeration control strategies and allows the engineer to conjointly investigate interactions between and effects on the biological and physical systems. It is proposed that by being able to simulate both the biological activated sludge system, and the physical/pneumatic/mechanical aeration system the following efficiencies will result:

→ Provide more "proof" of the efficacy of a proposed control system for a particular treatment plant biological and aeration system by being able to simulate system specific characteristics of each, and reduce the approximations involved.

→ Observation of the dynamic overall system characteristics to gain a better understanding of how the dynamic responses in the systems affect each other

→ Design of advanced aeration control systems taking into account more of the realities of the physical system

→ Design and optimisation of air delivery blower and pipework systems

→ Optimisation of energy use at a plant

It is not possible to do this fully within the confines of commercially available biological simulators, as they are not designed for the investigation of detailed control, mechanical and pneumatic effects of an aeration system. However, commercially available process simulation software that is specifically designed for this purpose does exist. Recognising this fact, CH2M Beca decided to investigate the feasibility of developing an interface between the two types of commercially available software packages and running them simultaneously to investigate these dynamic effects and interactions. To this end, an interface has been developed between GPS-X, a biological simulator, and IDEAS, a process simulator.

2 SIMULATION SOFTWARE

2.1 GPS-X

2.1.1 THE SOFTWARE

GPS-X is proprietary software developed by Hydromantis Inc. Like other commercially available simulators of this nature, it uses standard and widely accepted biological models to simulate the behaviour of activated sludge organisms involved in wastewater treatment. The GPS-X suite of biological models includes the ASM family, Mantis and New General models. GPS-X is open source software, meaning that the user can alter or extend these models if necessary (for example, with non-standard industrial influents). In addition, the software package provides the facility for the user to program the model with additional variables or equations in order to simulate plant specific conditions as necessary. In this way quite detailed plant operational strategies can be input to the model, effecting a more accurate simulation of mass transfers throughout the process.

2.1.2 OXYGEN DEMAND AND TRANSFER

BIOMASS OXYGEN DEMAND

Heterotrophic and autotrophic bacteria require oxygen for energy as they utilise organic carbon or ammonia as a substrate in growth processes for endogenous respiration, in some cases to uptake excess phosphorus. All of these processes can be accounted for in activated sludge models. Standard rate equations for these processes have been widely published.

OXYGEN TRANSFER

In GPS-X, the model user can select from a variety of choices with respect to the type of aeration that is to be simulated (diffused, mechanical), and how it is to be approximated (using an entering airflow, a mechanical transfer rate). However, the equation used by the GPS-X software governing the oxygen transfer to the liquid phase is the same regardless of these choices:

$$V\frac{dC_L}{dt} = QC_{IN} - QC_L + K_L a(C_\infty^* - C_L)V + rV$$

Equation 1: Simulation of Oxygen Transfer in GPS-X

Where

V = reactor volume (m3)
C_L = concentration of Dissolved Oxygen (DO) in the reactor (mg/L)
C_{IN} = concentration of DO entering the reactor (mg/L)
Q = influent flow rate (m3/d)
K_La = oxygen transfer coefficient at field conditions (L/day)
C^*_∞ = DO saturation concentration at fields conditions (mg/L)
r = rate of use of DO by biomass (g/day)

From this it can be seen that as would be expected, the major effect on DO concentration in the biological system will come as a result of the rate of biomass oxygen consumption. The physical aeration system is not taken into consideration, and the software assumes a 100% efficient airflow delivery system. The model developer can adjust coefficients and other factors to take into account of some aspects of the physical system, for example adjusting shaft power ratings for mechanical aerators or adjusting alpha factors for diffusers. In this way, the level of DO in a bioreactor can be reasonably simulated, and the biological process analysed.

2.1.3 LIMITATIONS

The limitations of biological simulation models with respect to influent and process biology have been the subject of many publications, and are not included in this discussion. The specific limitations of the software with respect to an accurate representation of the physical aeration system include the assumption of an ideal air delivery system, and no ability to assess the dynamic effects of one system on another. From a controls perspective, any variable can be used as a control variable, regardless of whether this could realistically be implemented. Writing code into the model is time consuming, and the inbuilt controllers idealised. All these factors mean that while GPS-X is suitable for generic studies, process research, and for the assessment of simple control systems where experience can be used to judge the suitability for full-scale application, a level of uncertainly is introduced when considering advanced control systems coupled to non-ideal aeration systems.

2.2 IDEAS

2.2.1 THE SOFTWARE

In many process industries, simulation of both the reactive process and the control system is done in the same package, though the possibilities for dynamic modelling control can be limited. The IDEAS Simulation and Control package by Andritz Automation has been designed to simulate to a high level of fidelity the result of the control of pressures and flows of compressible and incompressible gases and liquids within plant systems. It has been used within the Beca group to develop detailed control systems for diverse industries such as pulp and paper and fertiliser processing. For activated sludge diffused aeration systems, it also provides a means of simulating the physical aeration system of the plant, from the blowers through a replicated series of pipes and control valves to the diffusers. In IDEAS, systems are put together consisting of 'blocks' that represent a particular object, for example a valve, pipelength, pump or compressor. Where there is no existing block for a particular object, the model developer can create this.

PHYSICAL ASPECTS

Two new blocks needed to be created to simulate the air blower and diffusers in an aeration system. Specific blower characteristics were approximated by using a generic centrifugal pump and valve block, and adjusting parameters so the block's output mirrors the actual blower curve. While there is no generic diffuser block, it was found that by using a generic control valve block connected to an equation block which in turn provided the setpoint to a rapid response PID provided an accurate reflection of the pressure/flow aspects of the specific type of diffuser installed within the plant.

AIRFLOW ASPECTS

Airlow and pressure within pipes are computed by solving a large number of differential equations with every step of the simulation. For particularly complex models, convergence to realistic values can take some time, however simulation is always much faster than real time. Efficient use of processing power became an important factor, as the same computer ran both GPS-X and IDEAS concurrently, with Microsoft Excel as an intermediary parameter link, outlined further in the next section.

CONTROL ASPECTS

As has been mentioned, IDEAS has built-in PID and equation blocks to simulate accurate control of the plant. Cascading of PIDs is possible and a specific type of control valve can be simulated by using a generic control valve and adjusting parameters accordingly, then attaching the output of one PID block to the others input.

LIMITATIONS

While it is possible to accurately model the physical setup of the plant down to the smallest pipe diameter, it is recognised that not every idiosyncrasy of a plant's aeration system will be perfectly reflected. For instance, one challenging aspect is the number of manual valves typically spaced throughout the aeration system that have no positional feedback and are adjusted by operators to ensure the smooth running of a plant.

Similarly to GPS-X and the biological process equations that it uses (or indeed any simulator of any type), for all the technical complexity of the software, the simulated flows and pressures have been derived from a series of theoretical equations, calculated for ideal conditions and therefore judgement and experience is required when using the simulator. With respect to activated sludge plants, the major limitation is of course that the software does not include the facility for biological simulation.

2.3 THE BIG IDEA - COMBINING THE SOFTWARE PACKAGES

Each software package is restricted to passing and receiving the variables that are most appropriate to its functionality. Therefore GPS-X is passed the airflow from IDEAS, and from this calculates the oxygen transfer. In conjunction with the oxygen uptake rate of the biomass, this allows the calculation of DO in the bioreactor. GPS-X then passes the DO (or any other control variable) back to IDEAS, where the simulated control system receives these as setpoints or part of a control algorithm. This is demonstrated in the Figure 2. In order to achieve this, it was necessary to develop an interface between the two packages and to test its functionality prior to attempting to build a combined model of a full-scale plant.

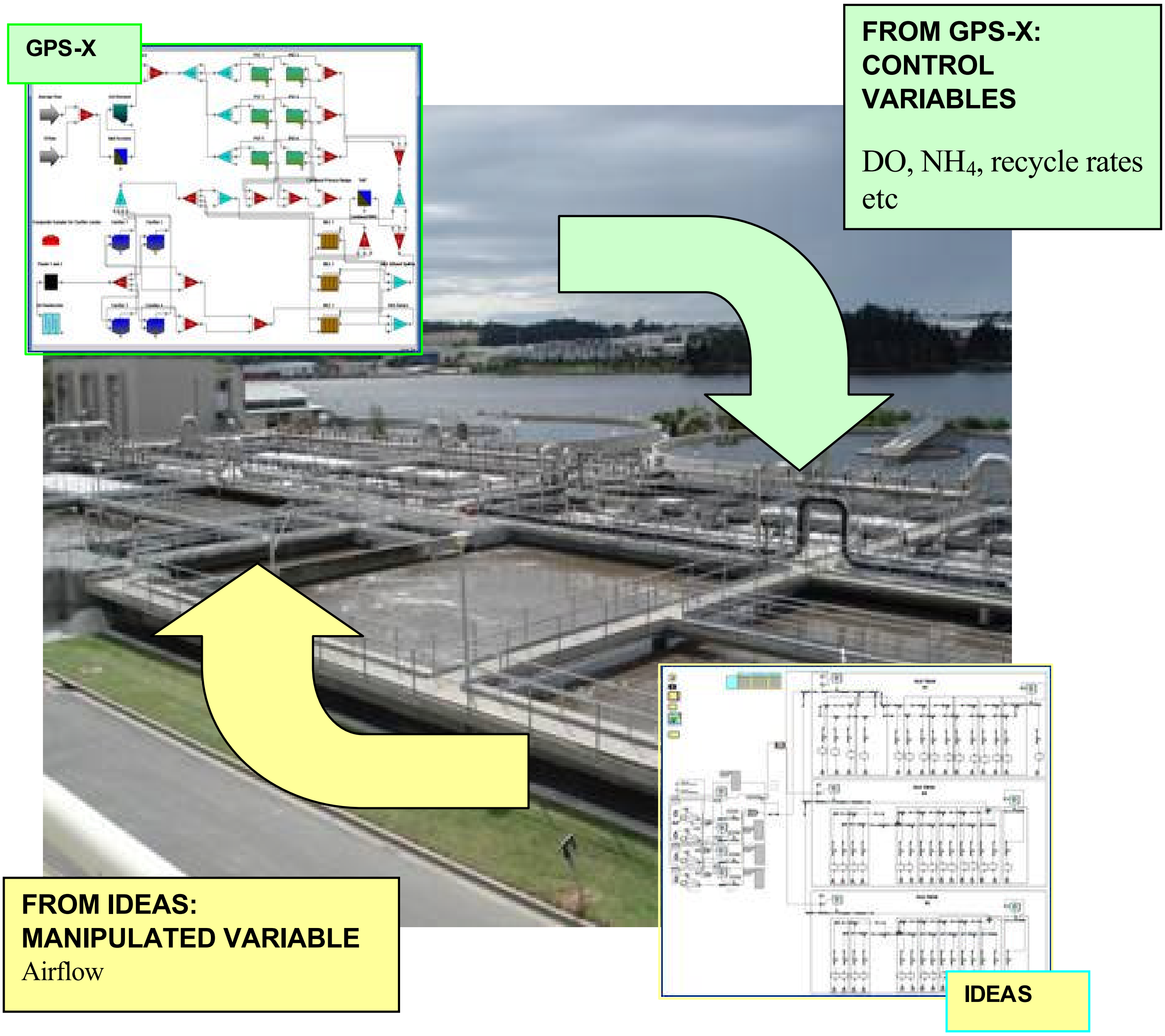

Figure 2: The big idea - how GPS-X and IDEAS interact

3 DEVELOPMENT METHODOLOGY

3.1 TEST MODEL

The purpose of the test model was to establish the interface between the simulators, and also to establish that the response of the IDEAS model was correct in terms of adjusting an airflow rate to compensate for a disturbance in DO control variable from GPS-X.

3.1.1 GPS-X TEST MODEL

The model used for initial testing was one of the default layouts within GPS-X, 'nitrifying/ denitrifying plant', a simple Modified Ludzack-Ettinger (MLE) configuration shown in Figure 3 below. The default influent, recycle and sludge wasting parameters were used. No aspects of the model needed further development. Obviously, the model did not come with a specified physical aeration system, so it was necessary to invent one for the initial testing! This meant that the airflow split to each aerated zone needed to be specified in GPS-X, rather than being a natural function of the aeration pipework and calculated by IDEAS. The selected control variable was DO.

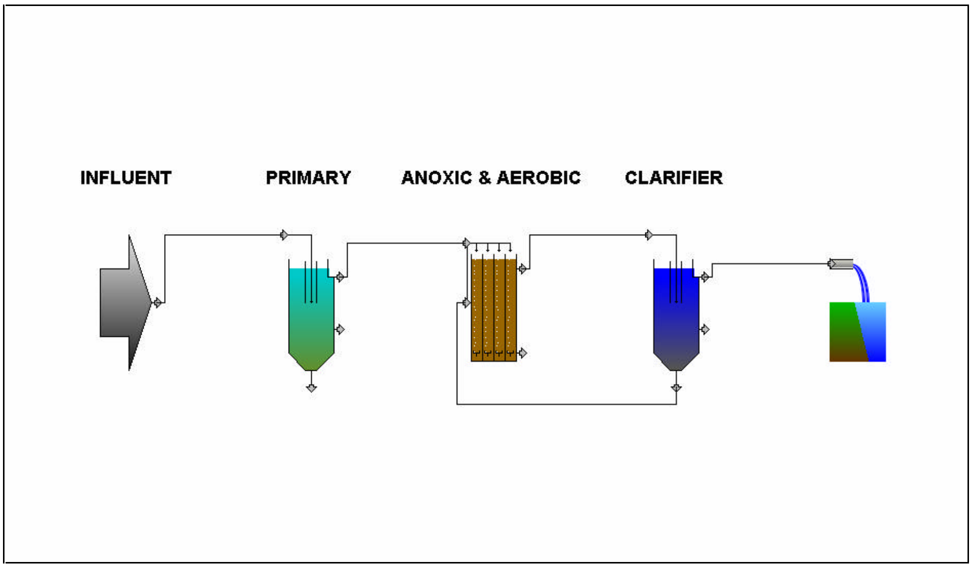

Figure 3: GPS-X test model

3.1.2 IDEAS TEST MODEL

The IDEAS test model developed for the initial stage of the project is shown in Figure 4. It consists of a blower block, pipework, control valve and diffuser. The blower and diffuser blocks were created for this model.

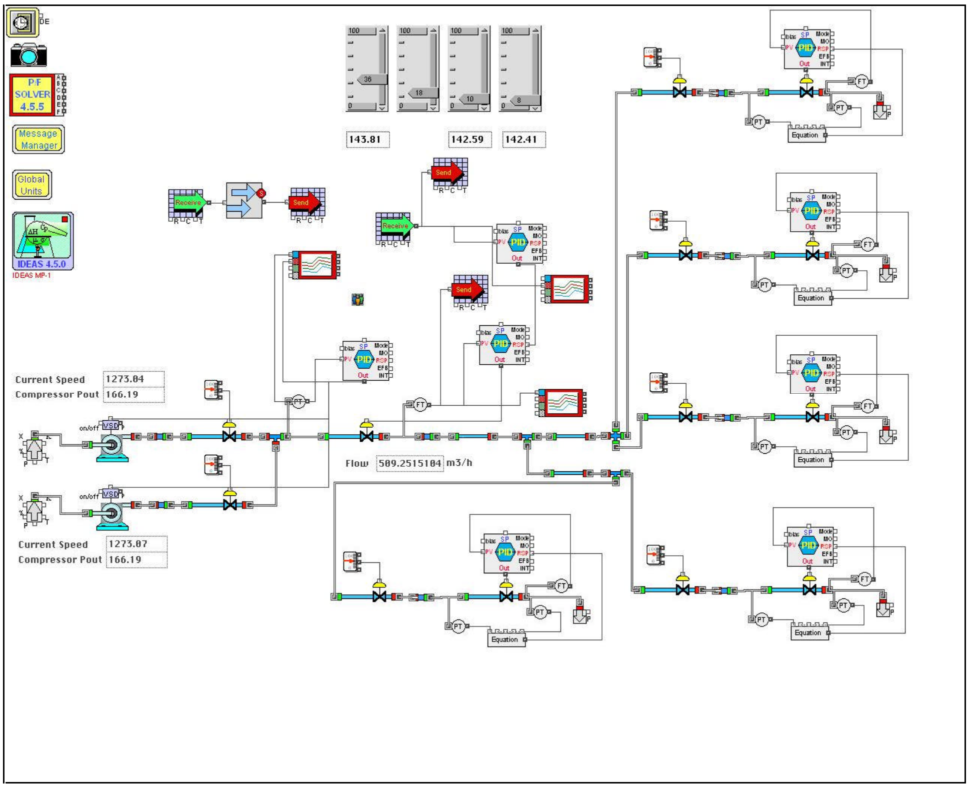

Figure 4: IDEAS test model

BLOWER BLOCK
Blowers in IDEAS can be represented in a number of ways. The most simple is to represent a blower as a 'Stream Source' of constant flow. More complex variations can use the 'compressor' or 'gas mover' blocks and edit various parameters within these blocks to create a fair estimation of the actual blowers being used. Because the generic blower-type block parameters did not allow us to implement the blowers with diffuser vanes as accurately as was required, a compressor block was used alongside a damper block.

A blower changes its flow output depending on the header pressure. This relationship is described by a fan curve, typically shown by any one of the curves in Figure 5. Typically blowers are manufactured to meet a client's specific needs and therefore have individual curves. Given the maximum and minimum flows and header pressure, and knowing the general shape of the fan curve, it is possible to impart a relatively accurate blower curve to the simulation software.

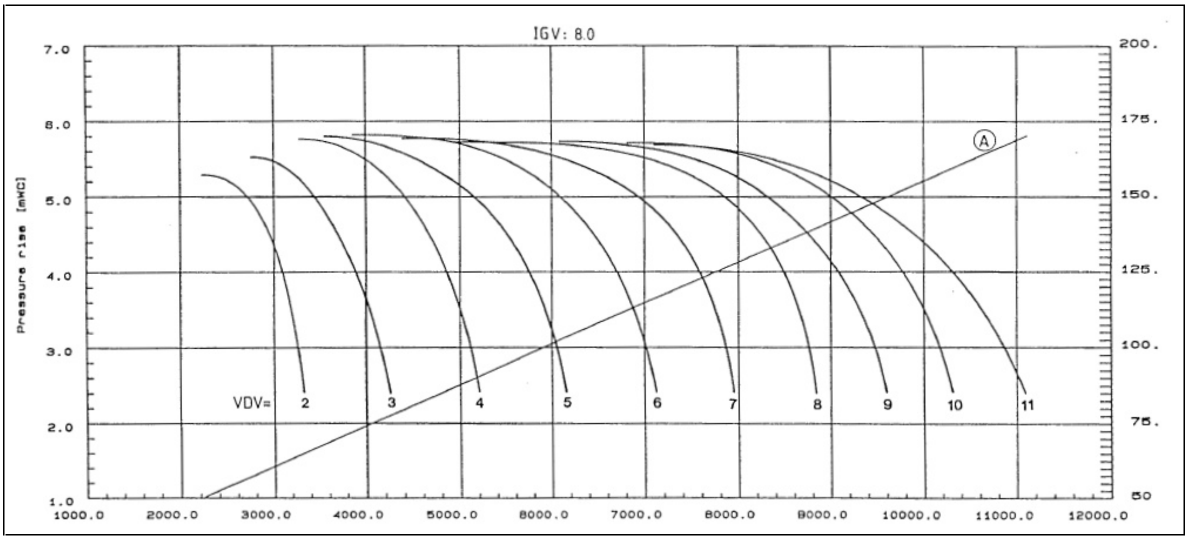

Figure 5: Fan Curves for different vane positions in a HV Turbo Blower

A centrifugal blower can include a vane system, which consists of a number of adjustable radial blades which, when adjusted, change the fan curve of the blower. This allows the blower to be turned down to 45% of output capacity with little loss of efficiency. This is simulated in IDEAS by a damper block.

DIFFUSER BLOCK
The diffuser block was created to simulate the airflow and pressure drop for an Aquablade membrane diffuser that is manufactured by Aquatec-Maxcon. Using the specified tested values of back pressure ($\Delta P = Pressure_{IN} - Pressure_{OUT}$) and airflow ($m^3$/hr) and entering these values into an excel spreadsheet, graphing them and then using the Excel trend function, a non-linear equation for the line was found relating Airflow to ΔP, as shown in Figure 6.

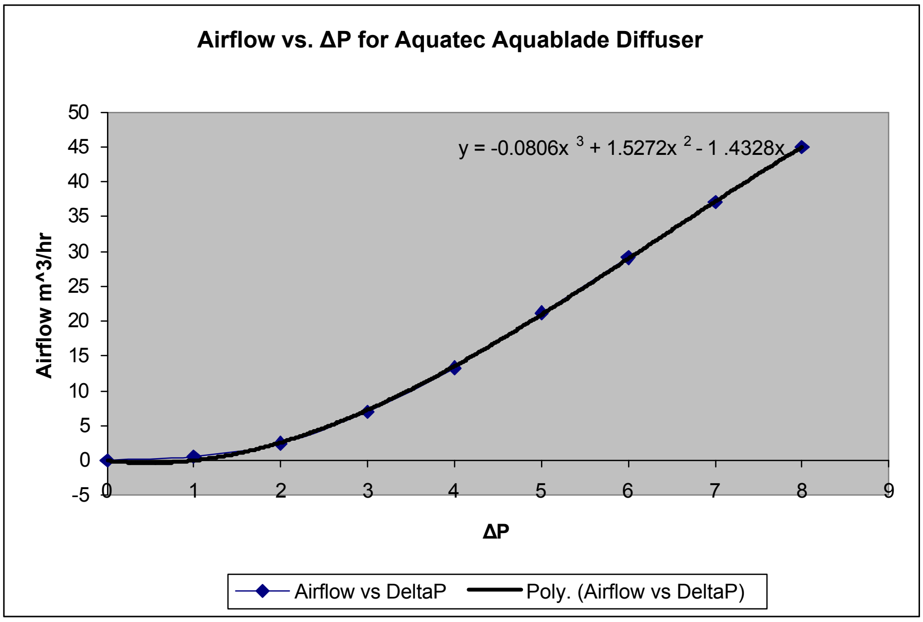

Figure 6: Airflow vs. ΔP for Aquatec Aquablade Diffuser. The heavy black line is the Excel trend polynomial function (Poly.) that fitted the Aquatec data.

The diffuser model (Figure 7) was created using a valve that had a linear airflow vs. valve open percentage with a PID block that did not include a derivative part. ΔP is calculated inside the equation block by subtracting the pressure before the valve and after the valve. The relationship between ΔP and airflow is regulated by how far the linear valve is opened. This is controlled by a PI controller using a set-point (SP) of the correct airflow for the current ΔP from the equation block, and a process variable (PV) of the actual airflow that is being measured out of the valve.

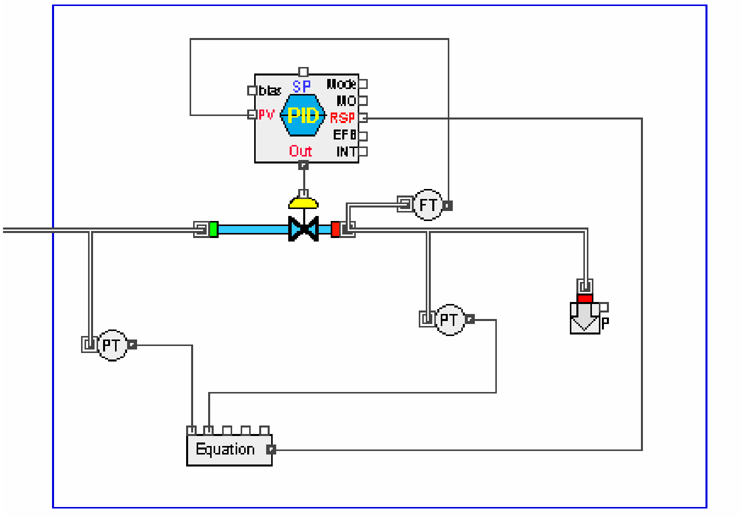

Figure 7: Final Diffuser Model. This model simulates the airflow and pressure drop of a diffuser using a linear valve and equation block.

3.2 INTERFACE DEVELOPMENT

There has been no previous attempt to link these two applications to our knowledge. Both had DDE functionality, but there were difficulties in consolidating communication between the two packages. Mainly for this reason, Microsoft Excel was brought in as an intermediary. Variables passed between the two packages are first placed into a Microsoft Excel spreadsheet then are sent by Excel to the other application.

An area that required attention was the synchronicity of the two applications. Both simulators are designed to run as fast as possible. GPS-X was resistant to attempts to control its speed of simulation on the fly, so IDEAS package is made to run slightly faster than GPS-X and slow down to wait for GPS-X if it gets ahead.

3.3 COMBINED MODEL

A schematic outlining the aeration control basis of the combined model is shown below (Figure 8). The airflow split to each aerated zone of the MLE is specified in GPS-X. Two DO probes are simulated in the first and second aerated zones. The names of the variables passed from GPS-X to IDEAs, and vice versa are shown.

GPS-X CONTROL

The GPS-X model was initially ran using the inbuilt DO control option, without IDEAS. By doing this, the required airflow at steady state and under the inbuilt diurnal flow and load fluctuation could be established. This gave terms of reference by which the combined model performance could be assessed. The limitation of this approach was that each of the 5 aerated basins would be controlled to maintain a certain DO setpoint in that basin, whereas the combined model would use only two DO probes to maintain setpoints in two aerated basins. The DO in the other basins would be determined by the airflow split.

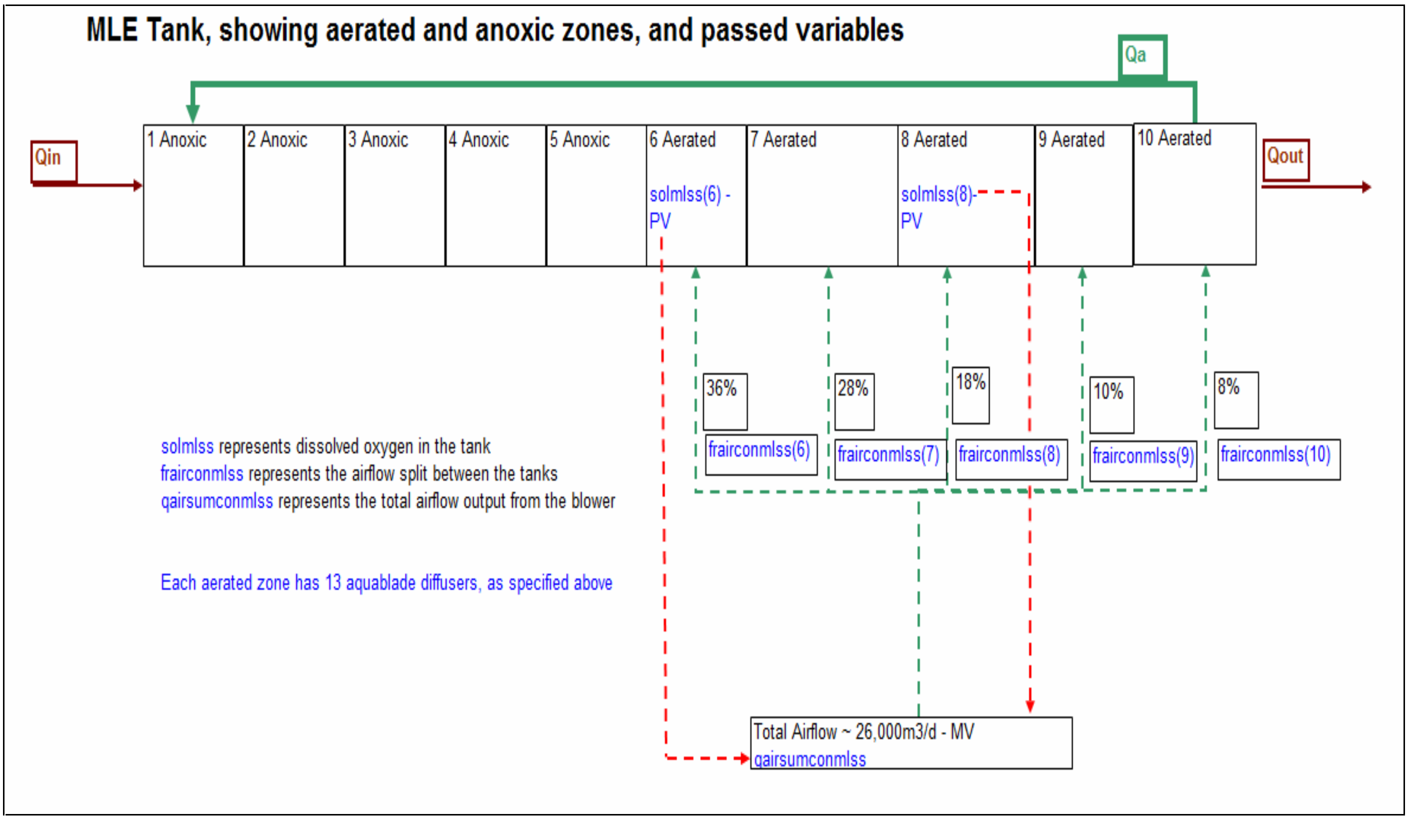

Figure 8: control basis of combined test model

COMBINED MODEL CONTROL

Once the reference airflow and other information had been collected from GPS-X alone, the combined model was run. Under steady state conditions, the model quickly reached an airflow that was very similar to that with GPS-X running alone.

Under dynamic conditions the airflow profile was similar, (Figure 9) showing that the interface and control functionality of the combined model worked.

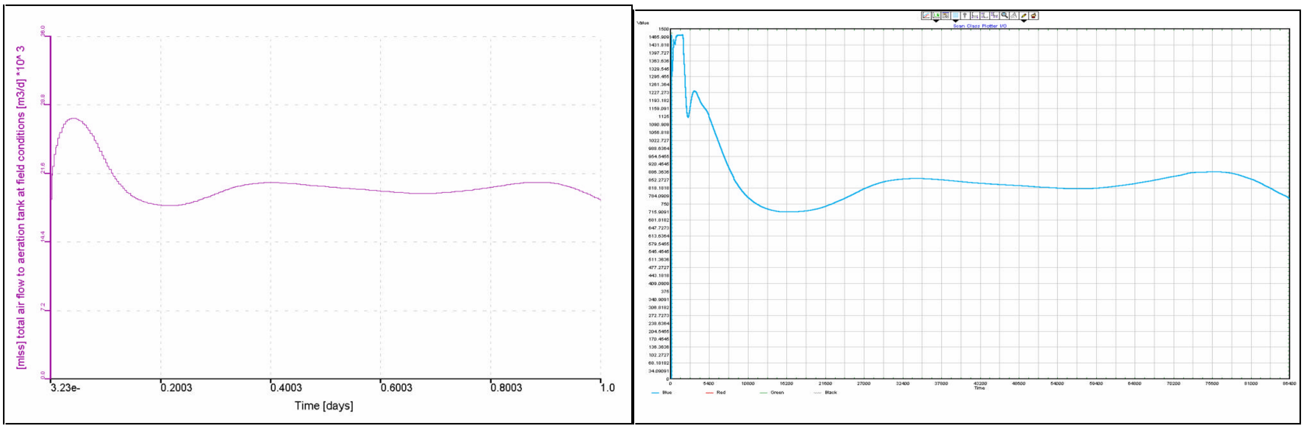

Figure 9: Airflow using GPS-Z alone (left) and the combined model (right)

The effluent quality from the two simulations is shown in Figure 10 below. When the combined model is running, the effluent nitrate and nitrite is slightly lower than when GPS-X alone is controlling the DO, which is expected as the overall DO is lower in the combined model, as DO control is only based on maintaining a setpoint in two of the aerated basins. However, the effluent quality is very similar overall and shows the same level of bacterial activity treatment being simulated when the combined models are running.

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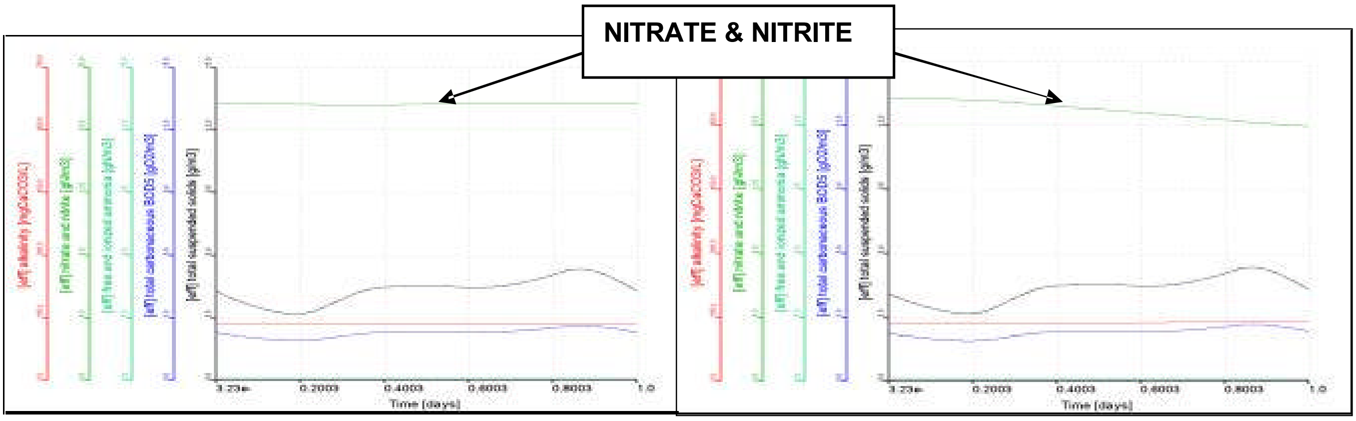

Figure 10: Effluent quality from the test model with GPS-X alone (left) and the combined model (right)

DISCUSSION

The interface between the two packages was functional, although slow. The combined model was sound in that communication between the packages had been established, and that IDEAs was responding to GPS-X in terms of adjusting an airflow rate to maintain a setpoint. At this point it became necessary to build a combined model of a full-scale plant in order to simulate a real diffused aeration system.

4 FULL-SCALE CASE STUDY

4.1 ROSEDALE WASTEWATER TREATMENT PLANT

Rosedale Wastewater Treatment Plant is owned and operated by North Shore City Council. The plant currently services a population of 225,000, and the catchment does not contain significant industrial waste discharges. The biological plant consists of three MLE bioreactors. The plant is designed to remove carbon and nitrogen.

4.2 MODEL DEVELOPMENT

4.2.1 GPS-X

A calibrated GPS-X model of the plant already existed as a result of previous work by CH2M Beca. The model was simplified to reduce the GPS-X calculation time by removing the Primary Sedimentation Tanks (PSTs) and sludge handling. Plant staff collected dynamic effluent data from the PSTs so that a representative post-PST influent characterisation could be developed. One of the advantages of using Rosedale as the basis for the model is that the plant does not suffer from highly variable trade waste influents as do plants servicing catchments with a large industrial component and therefore a limited amount of dynamic data was considered sufficient for initial testing and calibration. In addition, during the previous work, particular quirks of the plant aeration system had been noted and it was desired to see if the combined model could simulate these.

4.2.2 IDEAS

Plant data in the form of pipe diameters, lengths and layouts were used to create the mechanical side of the aeration system. Historical data in the form of blower currents, pressure and flows measured at various points of the plant, and control aspects such as control valve CVs and positions at various flow rates were collected to provide specific real data to calibrate the model.

There were three stages to converting the aeration part of the smaller generic model to one simulating the aeration system of the Rosedale Wastewater Treatment plant. First, the mechanical aspect of the model was implemented by putting together pipes, valves and blowers with their specific parameters to reflect the layout of the Rosedale Plant. Secondly, the control of the aeration system had to be added in a way that reflected the automatic control of the Rosedale plant. Copying the mechanical aspects of the plant down to the last short pipe length and diameter had to be balanced against how much more accuracy this would bring, adding unnecessary complication to the model and stretching the calculation capabilities of the software itself.

The control aspects of the blower system was created to reflect the plant functional description, and then verified by comparing to the actual plant PLC code. Each control valve has a PI controller linked to it that was tuned to reflect real plant data. In the Rosedale model cascading of PI controllers is used to control the opening of the main control valve dependant on the DO level passed back from GPS-X, and the current flow through the valve itself.

4.2.3 INTERFACE FUNCTION

The combined model interface was a larger version of the test model. Figure 11 shows the airflow of the IDEAS model in response to the DO signal from GPS-X. The control system simulated in IDEAS managed to successfully maintain the DO setpoint as specified by the Rosedale controls system. The blower response is accurate in that it simulates an increase in airflow in response to a drop in DO.

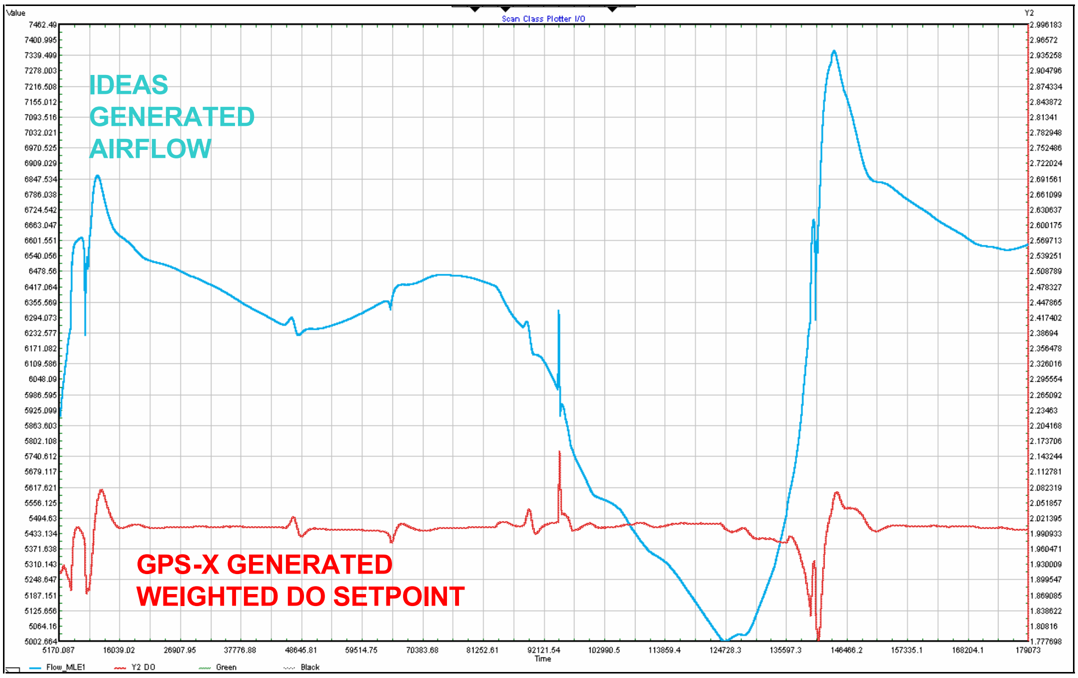

Figure 11: IDEAS simulated diurnal airflow profile

4.2.4 MODEL CALIBRATION

At the time of writing, the model is being calibrated and validated using dynamic data from Rosedale.

5 CONCLUSIONS

The combined GPS-X/IDEAS model is functional and was able to demonstrate the dynamic interaction that exists between the biological and physical aeration systems in an activated sludge plant. The full-scale Rosedale model is being calibrated and will be used to investigate different aspects of the aeration system that require this level of detail.

ACKNOWLEDGEMENTS

A huge thank you to all the operations staff at Rosedale Wastewater Treatment Plant.

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