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iEMSs 2008: International Congress on Environmental Modelling and Software
Integrating Sciences and Information Technology for Environmental Assessment and Decision Making
4th Biennial Meeting of iEMSs, http://www.iemss.org/iemss2008/index.php?n=Main.Proceedings
M. Sànchez-Marrè, J. Béjar, J. Comas, A. Rizzoli and G. Guariso (Eds.)
International Environmental Modelling and Software Society (iEMSs), 2008

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Abstract: Over a decade ago, the concept of a tool that could be used to objectively evaluate the performance of control strategies through simulation using a standard model implementation was introduced for activated sludge wastewater treatment plants. That concept resulted in the development of the Benchmark Simulation Model No 1 (BSM1), the subsequent BSM1_LT and most recently BSM2. Debate about the need and application of these models has dogged the development effort since it first began with practitioners suggesting that these models are only academically applicable, have been conceived of for publication generation purposes and provide limited benefit to the applied modelling community. The authors of this paper, as contributing members to the development, beg to differ with those detractors. The focus of this submission is the BSM models from the perspective of a modelling toolbox, and a platform, on which modelling issues have been debated, experimented upon, tested and developed to further the field of wastewater treatment modelling in general.

***Keywords**:* benchmark, BSM, modelling, activated sludge, anaerobic digestion

BACKGROUND

The Benchmark Simulation Models (BSMs) have been under development for many years through a cooperative effort involving research and corporate entities from around the globe. The initial reasoning for the development of these models was to create an unbiased tool that could be used to evaluate wastewater treatment control strategies (Spanjers et al., 1998). At that time, the literature contained many published control concepts, but the methodology used to test or examine the strategy impact in each case was specific to that control strategy. That is, these publications tended to focus on the specific advantages of the particular strategy in question without necessarily highlighting some of the adverse or spin-off effects. Because the strategy impacts were not fully reported, the comparison of different published strategies was almost impossible. It was believed at that time that a simulation-based tool would provide a means to evaluate the relative merits of all kinds of dissimilar control ideas taking into account all the effects that the strategy might have on the treatment process. The development effort has been on-going ever since.

Numerous papers have been published on the various complete benchmark models and these have been presented elsewhere (Copp, 2002; Copp *et al.*, 2002; Rosen *et al.*, 2004; Jeppsson *et al.*, 2006). As there is insufficient space in this paper to fully explore all of the tools that will be highlighted here, the reader is referred to these publications for more details. Publications by researchers, operators and consultants have all illustrated the use of the benchmark systems for the assessment of process performance and control system evaluation. However, the benchmark effort is not without its critics. The unit process sizes and model choices, influent characterisations, model transformations and evaluation criteria have all been criticised. Some of the criticism is justified as the defined BSMs have not always taken into account the most recent advancements or accepted theory, but the critics fail to fully appreciate the benefits generated by the effort, the debates, the compromises and the solutions that have gotten the BSMs to this point. The BSMs are not all-encompassing tools to be used only as fully defined nor are they 'best-practice' tools to be interpreted as showcasing the best models for specific unit processes. To limit the BSM application this way would be a shame. Rather, these models should be considered as collections of modelling tools that address various aspects of whole-plant wastewater treatment modelling. The value of these modelling tools is much greater than the value of the BSMs as fully defined and the modular nature of the tools means that they can be used in isolation if the need arises.

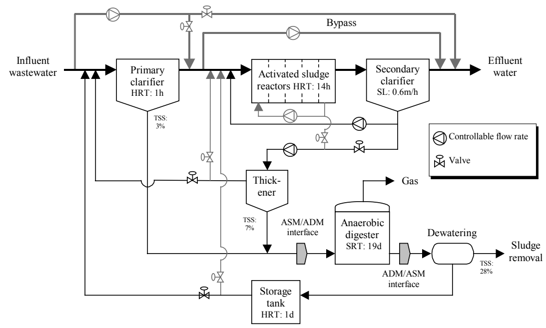

Figure 1: Plant layout for BSM2.

The BSMs contain a whole series of these modelling tools including but not limited to: an influent wastewater generating model, a temperature model, standard and ring-tested implementations of activated sludge model #1 (ASM1), anaerobic digestion model #1 (ADM1), the Takács double exponential settling model and the Otterpohl/Freund primary clarification model, anaerobic digestion/activated sludge model interfaces, empirical solids/liquid separation models, performance indices, operational cost indices as well as models for sensors and actuators and for energy consumption by aeration and pumping equipment. These modelling tools have all come as a direct result of the BSM development. Without the BSM platform, a collaborative development effort on these tools might not have occurred. This submission focuses on these tools with an aim to demonstrate the value of the BSMs as a comprehensive modelling toolbox.

BENCHMARK SIMULATION MODEL #2

The Benchmark Simulation Model No 2 consists of a model representing a general WWTP, an associated control system, a benchmarking procedure and a set of evaluation criteria. The main components of BSM2 (see also Figure 1) are: primary clarification (based on Otterpohl and Freund, 1992) and Otterpohl *et al.*, 1994)); a five-reactor nitrogen removal activated sludge system (based on Henze *et al.*, 1987); secondary clarification (based on Takács *et al.*, 1991); gravity thickening; anaerobic digestion (based on Batstone *et al.*, 2002); dewatering; AD/AS model interfaces (based on Nopens *et al.*, 2008); a storage tank; and an influent wastewater generator model (based on Gernaey *et al.*, 2005; 2006).

BSM MODELLING TOOLS

Influent Wastewater Generating Model

The evaluation of control strategies in BSM1 is done based on three different 1-week long 'weather files', corresponding to dry, storm and rain weather disturbance scenarios (Copp, 2002). However, at the outset of the BSM2 development, there was a general consensus that a 1-week evaluation period was insufficient to evaluate WWTP controller performance, especially when 'slow' actuators, such as the waste sludge flow rate, are manipulated (Gernaey *et al.,* 2006). Within the context of the BSM2 development, several options were discussed including simply repeating the weekly disturbance scenarios from BSM1, collecting 'real' data from an operating facility or creating a mathematical tool that could be used to generate a user-defined influent. The latter approach was chosen for several reasons, but the main reason was that those involved in the development felt that the model approach would solve several key problems including: 1) it would give sufficient flexibility to manipulate the influent to suit the BSM2 requirements; 2) it would not be skewed by a 'real' event that may or may not have occurred in a 'real' plant; and, 3) it would be modular, which would allow this tool to be used in isolation outside of the BSM2 context. Figure 2 shows a schematic representation of the model developed by Gernaey *et al.* (2005) and Gernaey *et al.* (2006).

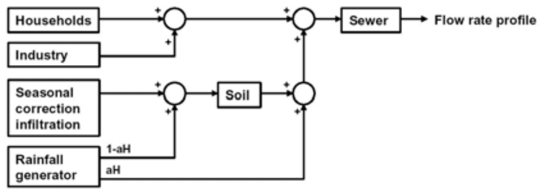

Figure 2: Schematic representation of influent generator model (Gernaey *et al.,* 2006).

The model (Figure 2) contains contributions from households, industry, rainfall and groundwater infiltration. Sub-models that include things like diurnal pollutant fluxes in the case of households, and weekend and holiday effects in the industrial model generate each of these contributing streams. These influent disturbance models allow the creation of influent dynamics that can include diurnal, weekend, seasonal and holiday effects, as well as rainfall. Being able to simulate these effects is important for control strategy evaluation, but this influent generator has far-reaching possibilities for the wider modelling community.

Temperature Model
The evolution of the BSM models has been an interesting study in modelling complexity as with each new addition has come several new challenges. The simulation procedure defined with BSM1 assumed a constant temperature of 15^{o}C. By extending the simulation period in BSM2, it was necessary to include changing temperatures in each of the streams and unit processes. Temperature has a recognised impact on the biological activity in the ASPs and digester and on the oxygen mass transfer in the ASPs. This, combined with a year-round warm return stream from the digester required that a temperature model be developed that might be used to estimate changing temperatures in each stream.

For points in the model where streams combine, several proposals were discussed from complicated heat balance models, to simple mass flow heat blending models. However, based on the fact that the BSM model is assumed to have a slow temperature dynamic, it was deemed reasonable to adopt the simple heat blending methodology. In this method, at points in the model where streams meet, heat mass flows are calculated with the total outgoing mass flow simply divided by the outgoing flow to give an estimate of the outgoing temperature. The fact that the more complicated models were rejected is no reflection on their application, but simply a further contribution of the BSM work in that both simple and more complicated solutions were discussed, debated and documented.

In addition to estimating the temperatures in the various streams, it was of interest to model the impact of temperature on the modelled kinetics and process parameters like oxygen saturation, oxygen transfer rates and by extension, energy for aeration. Typically the commercially available simulation packages have temperature models incorporated, but the BSM debate has highlighted that different relationships exist and in a general sense given them another option for these relationships.

Model Implementation Ring-Testing
One of the first highly regarded outcomes from the BSM development work was the ring-testing of several implementations of activated sludge model #1 (ASM1) and the Takács secondary clarification model. Computer simulation of wastewater treatment systems is a powerful tool, however, critical to the BSM concept is that any simulations carried out, any where in the world, using any simulator must be directly comparable to results generated everywhere else (Figure 3). This, therefore, required that the model implementations in each platform be exactly the same.

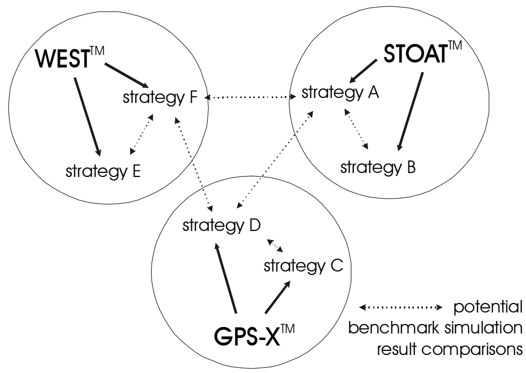

Figure 3: Illustrative representation of the comparison concept showing that in addition to comparisons being made between results generated with the same simulator, results from different simulators can also be compared.

In this case, ASM1 and the settling model were implemented into 5 commercial simulation packages (WEST, STOAT, Simba, GPS-X, BioWin) and 2 open code platforms (Matlab/Simulink, Fortran). Each of the simulator platforms had different specific features that made getting the simulators to produce exactly the same results difficult. Issues that were discovered included things like aeration model differences, simulator-specific model alterations, and also errors in the model code. Each of these differences was investigated and 'corrected' so that each simulator eventually produced the same steady state result. This steady state investigation was followed by a dynamic simulation test and here again, simulator-specific issues resulted in different dynamic results. The most prevalent problem identified at this stage was the implementation of the settler model as each package seemed to handle the clarifier's soluble components a little bit differently. Nevertheless, after nearly 2 years of work, the BSM co-operative effort had ring-tested 7 ASM1 implementations, 'corrected' any differences and achieved the same results (to several decimal places) in all platforms (Copp, 2002) proving that it was possible to achieve the same results in all platforms, but exceptional care must be taken to do it. The importance of this aspect relates to the goal of the simulation benchmark development; namely, the development of a platform independent standardised evaluation protocol, but in the larger context, this work has resulted in debugged ASM1 model code. The commercial simulators now include this ASM1 implementation in their packages so users can be assured that when using ASM1 (or the Takács settling model) in one of these packages they are using a fully tested and verified version of the model.

A similar exercise was carried out for ADM1. ADM1 (Batstone *et al.*, 2002) was implemented into the simulation packages and tested in the same way as previously described for ASM1. Similar results were found in that each simulation package required special considerations, but after these simulator-specific issues were identified, each package gave the same results (again to several decimal points). In the case of ADM1, the model had to be modified for BSM2 to optimise the simulation performance. An important difference between the ADM1 of Batstone *et al.* (2002) and the ADM1 for BSM2 is the introduction of continuous inhibition functions for pH to avoid simulation problems related to discontinuities. In Batstone *et al.* (2002), it is suggested that ADM1 be implemented as a differential algebraic system, with algebraic equations for the acid-base equilibrium (although differential equations are also given in the report). This is, however, not sufficient to remove the stiffness of the system as it was discovered that the hydrogen state is much faster than the remaining states. Therefore, an algebraic solution for the hydrogen state was implemented for BSM2. This is an important finding as the *error* introduced by this change is insignificant yet this change is critical for some simulation platforms that need to use non-stiff solvers to handle the noise and discrete events that have been introduced for realism in BSM2. Detailed descriptions of the BSM2 implementation of ADM1 are given in Rosen *et al.* (2006) and Rosen and Jeppsson (2006). As with ASM1, the BSM work has generated a standardised implementation of ADM1 and resulted in a speed enhancement that makes this model more accessible and usable to the general modelling public.

The primary clarifier model (Otterpohl and Freund, 1992; Otterpohl *et al.,* 1994) chosen for BSM2 was also ring-tested. For the most part this was a new model to most of the packages so a standard implementation was easier in this case. As a contribution to the general modelling community, because it was a new primary model in most cases, the BSM effort has increased the choice of models for primary clarification where limited options were previously available.

Activated Sludge / Anaerobic Digestion Model Interfacing
Unfortunately (for wastewater treatment modellers) not all wastewater treatment unit process models have a common set of state variables which means that if two dissimilar unit processes are linked in reality and are to be simulated together in one model, a methodology for transforming the one set of states to the other must be developed (Figure 4).

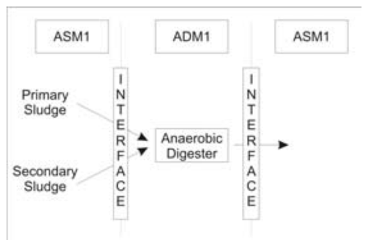

Figure 4: A conceptual representation of the interfaces needed to join dissimilar models.

The first benchmark model (BSM1) was comprised of the liquid treatment stream only, but BSM2 was expanded to include the sludge train which introduced a number of complicating issues; one of them being the coupling of ASM1 and ADM1. As this was crucial for BSM2 development, again the BSM team co-operated, debated and compromised to arrive at a reasonable solution for these transformations. An initial attempt at a transformation was made by Copp *et al.* (2003). The strengths and weaknesses of that approach were subsequently debated and a more advanced method specifically designed to account for differences in primary and secondary sludges in the digester was developed by Nopens *et al.* (2008) (Figure 5).

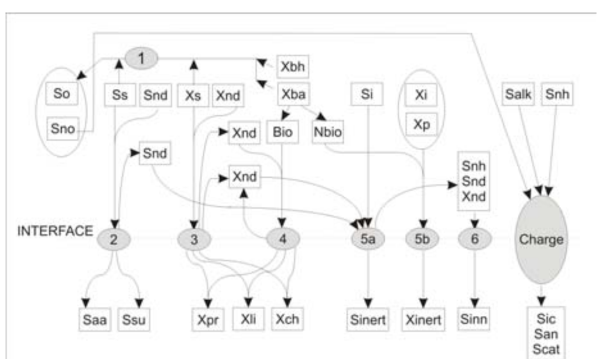

Figure 5: The BSM2 ASM1 (top) to ADM1 (bottom) interface.

However, more importantly to the general modelling community, this effort identified several deficiencies and spurred on further developments as several BSM contributors have since developed more generally applicable methodologies for interfacing all kinds of different models (Vanrolleghem *et al.*, 2005; Volcke *et al.*, 2006a).

Effluent, Cost & Risk Indices

Because simulations can generate an enormous volume of output data, comparison of that output data is difficult without some level of post-processing. The co-operative effort involved in the BSM development debated the merits of several options and settled on a performance assessment largely based on measures of general interest including:

- effluent quality
- operational costs
- risk

Effluent quality is considered through an effluent quality index (EQI), which is meant to quantify into a single term, the effluent pollution load to a receiving water body (Eq. 1) and operational costs are considered through an operational cost index (OCI) that includes seven terms.

$$EQI = \frac{1}{1000\,T}\int_{t_0}^{t_f}\left[PU_{TSS}(t)+PU_{COD}(t)+PU_{BOD}(t)+PU_{TKN}(t)+PU_{NO}(t)\right]Q_e(t)\,dt \qquad (1)$$

$$OCI = AE + PE + 3\cdot SP + 3\cdot EC + ME - 6\cdot MP + \max(0, HE^{net}) \qquad (2)$$

where PU_{xxx} is calculated as the product of β_{xxx} and the concentration of XXX at time *(t)*. The β_{xxx} factors were determined based, in part, on empirical effluent component weightings from a paper by Vanrolleghem *et al.* (1996) which cited a Flanders effluent quality formula for calculating fines. AE represents aeration energy (kWh/d), PE is pumping energy (kWh/d), SP is sludge production for disposal (average kg TSS/d), EC is external carbon addition (average kg COD/d), ME is mixing energy (kWh/d), MP represents methane production (average kg CH_4/d) and HE^{net} is the net heating energy needed to heat the sludge in the anaerobic digester. In the OCI case, the AE, PE and ME are in turn calculated based on more specific sub-models.

The pumping energy model has been modified several times over the years as new information and issues were addressed again reflecting the co-operative effort and compromises that have been adopted during the development. Initially the pumping energy was simply calculated as a constant number of kWh per m^3 pumped (the same for all streams), but this has since evolved into various ratios depending on the liquid being pumped (RAS vs WAS vs primary sludge vs….). As energy consumption becomes more and more important to the operation of treatment systems, these models could form the basis on which to estimate energy consumption and costs in any model.

To further enhance the objective evaluation of the BSMs a third type of performance index has also been developed: the risk index. This index adds a qualitative dimension to the otherwise only quantitative results from benchmark simulations. Based on a knowledge data base and fuzzy logic, a risk assessment of the simulated system is made, which estimates the risk of activated sludge system settling problems, e.g. filamentous bulking, foaming and rising sludge (Comas et al., 2006; Comas et al., 2008). The index is used to demonstrate that some control strategies, although performing better with regard to operating costs and effluent quality, induce a higher risk for solids separation problems. This is another module that can be used outside the scope of the BSMs.

Sensors and Actuators

In order to model any control strategy, sensors and actuators have to be modelled. For most modelling exercises, ideal (no noise, measurement error or time delay) sensors and actuators are used and in most cases this is sufficient. However, the reality of the situation is that sensors and actuators are not ideal. They are subject to errors and signal processing delays and possess particular dynamics due to the measuring principles (e.g. chemical reactions that must be completed within on-line analyzers). Models to describe these sensor and actuator behaviours have been developed within the BSM community and are now available for much wider use (Rosen et al., 2008).

To account for this, sensors in BSM2 can be ideal, but they can also be modelled based on the principles of Rieger *et al.* (2003). A number of sensor classes have been defined from which a benchmark user selects the ones most appropriate. Each sensor class includes characteristics such as noise level, time response, delay time, signal saturation levels and sampling time. All actuators are considered ideal except the aeration system, which is described using a simple model creating a delay in the K_La inputs and the reject water storage tank, which requires a somewhat more complex model.

Here again, modular sub-models within the BSM context have been created. As with all the other pieces included in the BSMs, these can be used outside the BSM context as required by the larger modeling community, thus giving that modeling community the option to include or not include these real-world issues in their sensor and actuator simulations.

LIMITATIONS

The BSM models have provided a basis for many debates regarding whole-plant modelling and have resulted in some very well-tested compromises, but as with any tool of this sort, there are limitations. The published models chosen for each unit process might not be the best ones in existence, the sizes of tanks and the influent used, might cause peculiar behaviour that would not otherwise happen in reality and lastly although these tools provide the best option for objectively evaluating all kinds of control strategies simulated anywhere by anyone, there still exists the possibility that strategies will not be comparable because of the various options available to the user. Care has been taken to eliminate as much of this as possible, but this possibility still exists.

CONCLUSION

The use of this modelling toolbox provides an excellent starting point for modelling and evaluating many systems. Examples of such applications have been recently presented by Volcke *et al.* (2006b) and Benedetti *et al.* (2006). These 'extensions' are an unquantifiable benefit of the BSM work and show that the BSM influence has not been restricted to control strategy evaluation alone but rather emphasises the importance of the effort to modelling in general. The inclusion of primary treatment as well as sludge treatment in BSM2 increases the complexity of the system but more importantly allows for the study of unit process interaction and has forced the benchmark team to develop and consider a new set of modelling tools that have far reaching implications and uses. The toolbox has been freely distributed to modelling groups on all continents to provide a structured, documented and validated starting point for their future work. Seeing beyond the narrow application of the BSMs as fully defined, should silence the critics and highlight the value of the modelling toolbox that has been created through a world-wide cooperative effort.

ACKNOWLEDGEMENTS

Many excellent researchers and close friends have contributed to the development of the BSMs over the years and the authors wish to express their sincere gratitude to all of them. The authors are also grateful for the support by IWA when establishing the BSM Task Group. Peter Vanrolleghem holds the Canada Research Chair in Water Quality Modelling.

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