New simulators for the optimum management and operation of wastewater treatment plant

E. Ayesa*, G. Garralon, A. Rivas*, J. Suescun**, L. Larrea* and F. Plaza****

*Section of Environmental Engineering, CEIT, P.O. Box 1555, 20018 San Sebastian, Spain

**Research & Development Department, CADAGUA S.A., P.O. Box 834, 48011 Bilbao, Spain

Abstract This paper presents the basic description and the first full-scale implementation of a new kind of simulator specially designed to facilitate and improve the management and operation of modern wastewater treatment plants (WWTP). This new kind of simulator for plant operation is specifically adapted to every WWTP and the software is developed considering the common needs of the operators in plant exploitation.

The internal structure of the plant operation simulator is based on a complete connection between the real data and the mathematical model of the plant. The software is then able to perform the processing, storage and management of the plant data and to predict the evolution of the process reading the required inputs from its stored files. The results obtained with the first application recommend the implementation of this new kind of simulators for plant operation in other treatment plants. However, it is important to note that the application of this technology implies a systematic and rigorous methodology in the acquisition and processing of the most significant plant data.

Keywords Data management; mathematical modelling; simulation; operation

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Introduction

During the last few years new advanced processes have been developed to improve the efficiency of the removal of organic matter and nitrogen in wastewater treatment plants (WWTP). These new processes are usually based on complex configurations with high flexibility and many selection parameters for the plant operator. The possibility of exploring different operational strategies using dynamic simulators of the WWTP will be one of the most helpful tools to improve the plant operation.

There are many simulators that have been successfully employed in design, plant diagnosis or selection of general rules for operation (Dupont and Sinkjaer, 1994; Suescun *et al.*, 1994; Dudley and Chambers, 1995; Gujer, 1995; Patry and Barnett, 1996). However, there are few software packages able to provide both real-time acquisition and predictive modelling. For this reason the practical implementation of the simulation programs to improve and facilitate the daily task of the plant operator has been limited. The main characteristics required for a simulator in order to be used in daily plant operation are as follow.

- The simulator for plant operations should be simple, user-friendly and adapted to the practical knowledge of plant operators.
- The introduction of plant data to the simulator should not increase the daily task of the plant operators.
- The plant model should be as descriptive as possible in order to reproduce in detail the characteristics and flexibility of the specific WWTP. This level of adaptation could be difficult to obtain using general purpose simulators.
- The simulator for plant operation should facilitate the periodic recalibration of the unknown model parameters using the real data (conventional analytical reports and on-line sensors).

Taking into account these requirements and the limitations of most conventional dynamic simulators, the engineering company CADAGUA and the Research Centre CEIT have developed a new kind of simulator specifically orientated to improving and facilitating the daily data management and the operation of the WWTP exploited by the company.

The simulator for plant operation

The concept of the simulator designed for plant operation is based on a specific program for every WWTP and a complete connection between the real plant data and the predictions based on the mathematical model. For this purpose, the simulator for plant operation must be physically implemented in the plant and must include two modules: the Data Manager and the Predictor.

Data Manager

The Data Manager is the first module of the simulator. It performs the processing, storage and management of the plant data and historic files. The heterogeneous information managed by this module can come from the conventional laboratory analysis introduced by the operator and the continuous information registered from the Programmable Logic Controllers (PLC).

- Laboratory data introduced every day by keyboard are the results of the common analytical procedures used to measure the state of the process in different points of the plant (COD, filtered COD, TKN, ammonia, nitrates, suspended solids, etc.). In general, the use of a simulator for plant operation does not increase the analytical effort required by the conventional plant exploitation.
- Continuous quality measurements from the sensors of the plant are automatically registered. These data are extracted from the PLC and, after noise filtering and sampling, automatically introduced in their corresponding places in the Historic Files. Typical quality measurements from the plant sensors are dissolved oxygen (DO), suspended solids, turbidity, ammonia, nitrate, temperature, etc.

All this information, stored in a formatted structure (Historic Files), can be easily used by plant operators for conventional data management (statistical analysis, plant supervision and reports). Additionally, the Data Manager creates condensed files (Input Files) that include all the information strictly required by the Predictor in order to simulate the dynamic behaviour of the WWTP during a selected period (influent wastewater characterisation, flows, DO levels, turbines, sludge wastage, etc.).

Predictor

The Predictor is the second module of the simulator, which performs the numerical simulations of the entire WWTP reading the required input data from the Input Files created by the Data Manager. The software requires a specific model including a very precise description of the different elements of every particular WWTP. The apparent increase in the effort required for software development can be significantly reduced using object-oriented libraries of the most typical plant elements (biological reactors, settlers, tanks, sluices, aeration systems, etc.). This modelling task has been based on the previous experience of the CEIT and CADAGUA S.A. in the development of simulators for WWTP (Suescun *et al.*, 1994; Rivas and Ayesa, 1997; Ayesa *et al.*, 1998).

The plant operator can use the Predictor for two main purposes: past-time predictions for model calibration or future-time explorations for optimisation of plant operation. When past data stored in the Historic files are used, the comparison of real and simulated measurements facilitates the diagnosis of the process and the periodic recalibration of the mathematical model. When fictitious inputs are introduced, the simulations can be used to explore the response of the plant to different influent loads or operational strategies.

A symbolic description of the described simulator for plant operation is presented in Figure 1, showing the interrelation between the Data Manager module and the Predictor module.

Pilot study at the Badiolegi WWTP

The described simulators for plant operation have been implemented in a small but complex WWTP called Badiolegi located near San Sebastian. The main objective of this application has been the full-scale verification of the developed technology and the analysis of its potential and limitations in other plants.

Description of the Badiolegi WWTP

The WWTP of Badiolegi is an A-B process for COD and nitrogen removal (Bohnke, 1990). Every line of the primary treatment (A process) is composed of a biological high-load reactor for COD removal and a settler. The secondary treatment (B process) includes two lines of a conventional predenitrification-nitrification process and the corresponding secondary settlers. The plant treats the wastewater of 35,000 in/eq.

Description of the simulator for the Badiolegi WWTP

The Data Manager module of the simulator for the Badiolegi WWTP performs the processing, storage and management of the plant data and Historic Files. There are two main kinds of data: the daily analytical reports and the continuous information registered in the PLC. Both of them are automatically processed, filtered and stored in the Historic Files. Sampling period for plant data has been selected in 1 hour (data from continuous measurements) or 24 hours (data from daily report). The Historic Files and the user interfaces have been developed in MS Excel and consequently the Data Manager module can use all the functions and possibilities of this commercial software for data management and calculations.

The Data Manager can also perform some calculations with the plant data. As an example, the continuous estimation of the Oxygen Uptake Rate (OUR) in the biological reactors of the Primary Treatment (A process) is obtained from the evolution of air flow and oxygen concentration stored in the Historic Files.

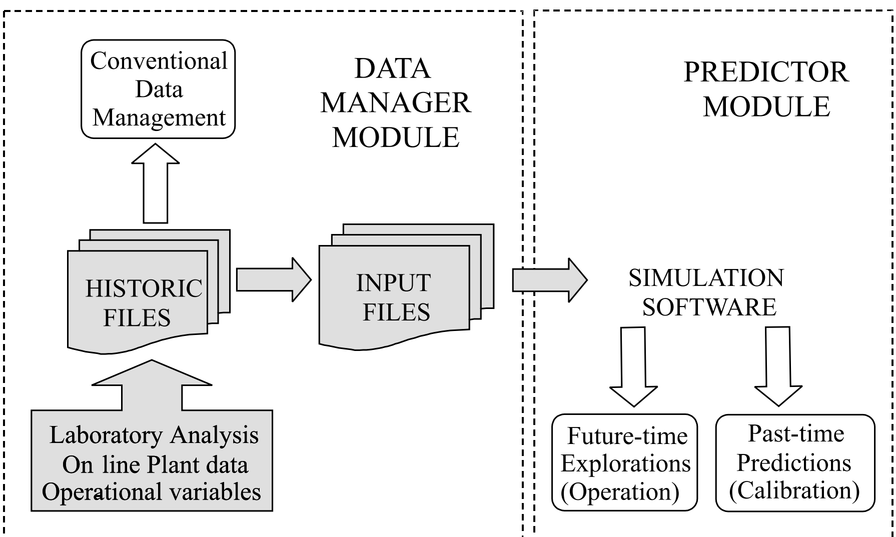

Figure 1 Schematic structure of the modules of the Simulator for Plant Operation

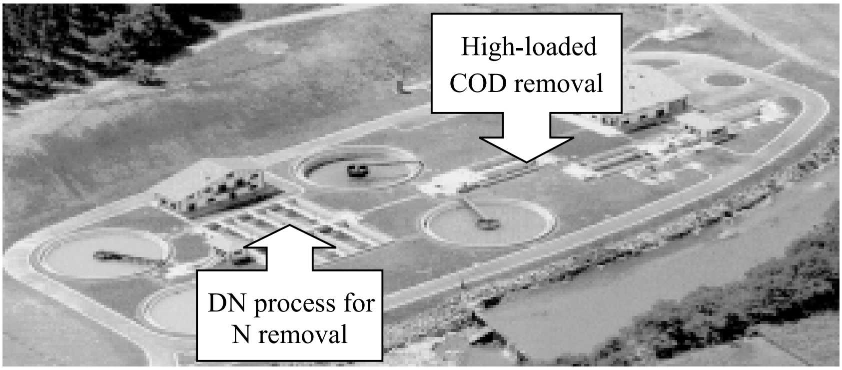

Figure 2 The WWTP of Badiolegi

The Predictor module is supported by a very descriptive modelling of the full plant based on the object-oriented library available at CEIT. The IAWQ model no 1 (Henze *et al*., 1986) has been the basis for the modelling of the biological reactors. However, a more descriptive fractioning of the COD, including rapidly hydrolizable substrate, has been required to describe the dynamic behaviour of the high-load Primary Treatment. Thickening in settlers has been modelled employing a simple mass-balance model developed in CEIT (Urrutikoetxea and Garcia-Heras, 1994).

The software of the Data Manager and the Predictor uses object-oriented programming and client-server structure (under COM). The Data Manager module, programmed in MS Excel, is called the client application and makes use of a server application that contributes the mathematical model of the plant. This server application, developed by CEIT in object-oriented C++, includes the modelling of the main elements of a WWTP and allows further reuse of the code in others simulators. The interfaces of the Data Manager and Predictor have been developed in Visual Basic to offer a user-friendly appearance to plant operators and managers (Figure 3).

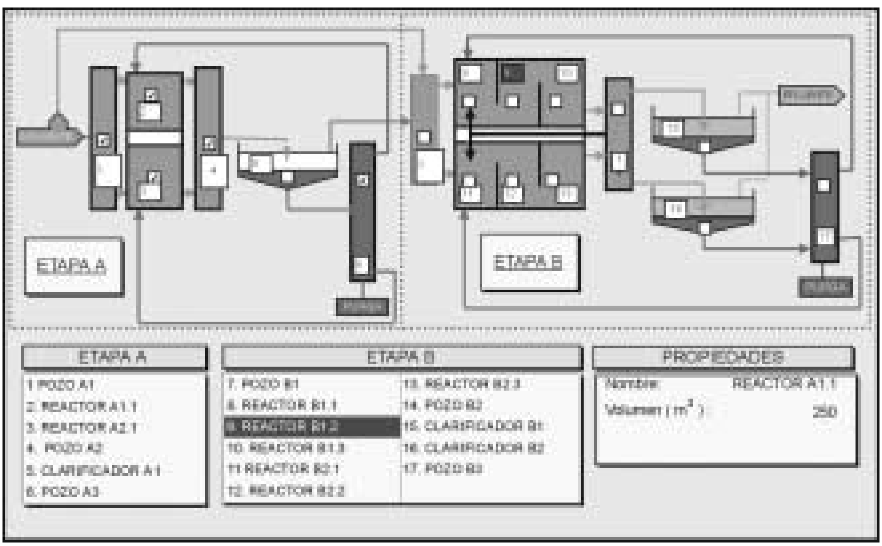

Figure 3 Appearance of the program interfaces for plant configuration

Results and discussion

The results of the Predictor of the Badiolegi simulator can be used for two main objectives: past-time predictions for model calibration or process diagnosis and future-time explorations for selection of the best operational practice of the plant.

Model calibration based on real data

The first step for an appropriate use of the simulator is the calibration of the unknown parameters of the mathematical model of the plant. For this purpose, the Predictor facilitates the comparison of the real measurements with the simulated values obtained when introducing automatically the corresponding input data stored in the Historic Files (influent load and operational conditions). Minimisation of residual errors by trial and error procedures is then used for the estimation of the unknown parameters during the selected simulation period.

Before trying to calibrate the model (influent fractioning and model coefficients) it is very important to test the quality and consistency of real plant data. Input files created by the Data Manager supplies to the Predictor all the information required for dynamic simulations. Then, a global analysis of these files is crucial to detect any error in data measurement or processing. There are two key points to be carefully tested by the operator: influent load (flow and concentrations) and solids wastage. Once this information has been tested, the normal procedure for plant calibration using the developed simulator has been:

1. Calculation and adjustment of the hydraulic balance and the internal flows around all the plant elements
2. Calculation and adjustment of the transport of solids around influent, effluent and waste flows
3. Wastewater characterisation (COD and nitrogen fractioning in the influent flow)
4. Adjustment of the biomass activity (kinetic coefficients of biodegradation models)

The first two steps are unavoidable to obtain good calibrations. Only once the hydraulic and solids predictions are adjusted, should the calibration of the unknown parameters of plant model be attempted. Wastewater characterisation consists basically of the estimation of inert and biodegradable fractions of COD and nitrogen and has been estimated in short-time periods (some days). Finally, the coefficients related to biomass activity have been adjusted over long-term periods to complete the precise calibration of the plant model.

Periodic recalibration of the model is based on the conventional data during normal exploitation without any additional measurement. A more intensive calibration procedure using full-scale data and lab analysis should only be used to establish the initial model coefficients or when persistent discrepancies between real and simulated data appear.

Results obtained by the Badiolegi simulator have shown a good agreement between real and predicted values maintaining the same kinetic coefficients of the model (at 20°C) and adapting the wastewater fractioning to the characteristics of influent flow for wet and dry weather. The numerical values of the coefficients of the biodegradation models are within the range proposed by the bibliography. Punctual discrepancies were generally caused by problems in the evaluation of hydraulic or solids balances but once the influent load and solids wastage was correctly measured, the predictions fit the measured data reasonably well.

As an example of the predictions of the calibrated simulator, some results from one month are presented in the next figures. Figure 4 (a and b) shows the correspondence of real and predicted concentrations of suspended solids in the biological reactors of the plant. Figure 5 shows the correspondence among the analytical results and predictions for the corresponding effluent quality in ammonia (a) and nitrates (b).

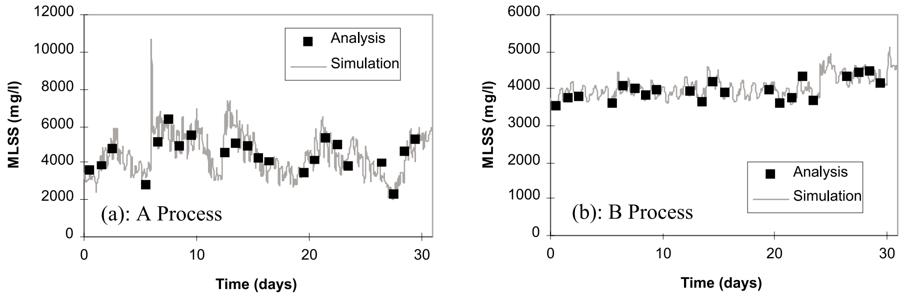

Figure 4 Real and predicted MLSS concentration in the biological reactors of the A process (a) and the B process (b) using the calibrated simulator

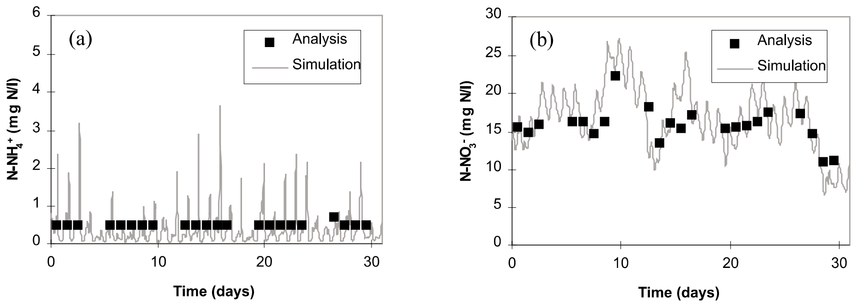

Figure 5 Real and predicted concentration of ammonia (a) and nitrates (b) in the biological reactors using the calibrated simulator

Optimisation of plant operation

Once the results of the Predictor module fit the registered real data during a selected period reasonably well, the model of the plant can be considered calibrated and the simulator can be used to explore alternative strategies for plant operation. All the influent characteristics and operational variables are read by the Predictor from the Input Files every hour. Then the operator is able to create any kind of fictitious scenario combining real and invented values in a case-study Input File. The Data Manager module includes some functions to facilitate the generation and management of these scenarios.

The simulator of Badiolegi WWTP is currently being used to analyse the effects of different combined manipulations of the operational variables in the effluent quality and in the exploitation costs. Possible implementation of controllers for regulating the concentration of Mixed Liquor Suspended Solids (MLSS) in the biological reactors by manipulation of waste flows (Suescun *et al.*, 2000; 2001) is being discussed. Additionally, maximum capacity of the WWTP for nitrogen removal and possible modifications to increase its performance are also under evaluation.

As an example of the practical use of the calibrated simulator, optimisation of nitrogen removal is currently being investigated. The specific limitation of the A-B process for nitrogen removal is normally associated with the low denitrification capacity in the secondary biological treatment when the removal of the biodegradable COD in the primary treatment is excessive. The simulator of the Badiolegi plant is currently being used to explore the effect of a partial by-pass of the influent wastewater flow directly introduced to the secondary treatment in order to increase the biodegradable COD available for denitrification. Additionally, the wastage of sludge from the secondary treatment must be increased at an appropriate rate in order to prevent an excess of MLSS concentration in the secondary biological reactors and an excess of solids load to the settlers. This increase in wastage will produce a reduction in SRT that can affect the nitrification. For this reason, this strategy should be used temporarily when high nitrate concentration produces poor sedimentation properties in secondary settlers. Some explorations with the simulator have been made to determine the global effect of the by-pass and its maximum admissible value.

Figure 6 shows the predicted concentration of ammonia and nitrates in the effluent of the plant when different percentages of by-pass (10%, 20% and 30%) of the influent wastewater to the secondary treatment are introduced in the Input Files. The rest of the input data are the real values stored in the Historic Files for the corresponding month except for the appropriate increase of sludge wasted to maintain the required MLSS in the secondary reactors. Analytical results presented in the figure are the real data observed in the plant without any by-pass.

The simulations show that the increase of the by-pass flow significantly reduces the nitrate concentration but can deteriorate the nitrification because of the reduction in sludge age associated with the increase of wastage. The maximum by-pass admitted by the plant during the analysed period is 10% of influent flow with a reduction of nitrate in the effluent of 3–4 mg/l.

Additional explorations based on the simulator are being made to study the effect of a partial by-pass only in the biological reactors of the A process (maintaining the primary settler) and the convenience of introducing an internal recycle in the secondary treatment not available at the moment.

Conclusions

The simulator of the Badiolegi WWTP has been the first full-scale implementation of a new kind of simulator developed by CEIT and CADAGUA S.A. to facilitate and improve the management and operation of modern wastewater treatment plants. The simulator is based on a complete connection between the real data and the mathematical model of the plant that facilitates the model calibration and the exploration of different operational strategies. Every simulator for plant operation must be specifically developed taking into account the characteristics of the application (data and models).

This first full-scale verification in the WWTP of Badiolegi has shown the possibility of implementing the simulator as a useful tool for plant management and operation without any significant increase in the analytical effort required for the conventional plant exploitation. When past data stored in the Historic files has been used in the simulations, the comparison of real and simulated measurements has facilitated the diagnosis of the process and the calibration of the mathematical model. When fictitious inputs have been introduced, the simulations have been used to explore and select operational strategies.

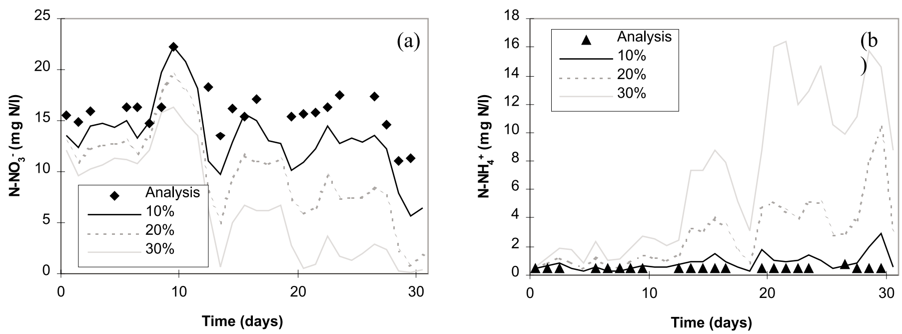

Figure 6 Effluent quality of WWTP predicted by the simulator of the Badiolegi plant when different percentages (10%, 20% and 30%) of the influent flow are directly introduced to the secondary treatment

The selected software structure (with MS Excel as the "client application") provide user-friendliness and powerful tools for data management and reduce the time required for further implementations to other bigger plants where the advantages of the simulator will be more noticeable.

The application of the simulators for plant operation in different WWTP suggests a new improvement from the conventional exploitation procedures, allowing the interchange of standard data files and the centralised supervision of many different plants. Other further research objectives are the automatic recalibration of the simulator from the real plant and the mathematical optimisation of the operational strategies according to a defined cost criteria.

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