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Editorial

The COST benchmark simulation model—current state and future perspective

Abstract

The paper introduces the philosophy and current status of a benchmark for the evaluation of control strategies in wastewater treatment plants and also the forthcoming developments and future perspectives. The work has been carried out within the framework of two COST Actions (682 and 624) and in close collaboration with the IWA Task Group on Respirometry. The benchmark is a platform-independent simulation environment defining a plant layout, a simulation model, influent loads, test procedures and evaluation criteria. Several different research teams have contributed to the development of the benchmark and have obtained results using several simulation platforms (GPS-X™, MATLAB/SIMULINK™, SIMBA®, WEST®, FORTRAN code, etc.). A short introduction to the six scientific papers of this special section dealing with various aspects of the COST benchmark simulation model is also given.

Keywords: Benchmarking; Control strategy; Modelling; Performance assessment; Simulation; Wastewater treatment

1. Introduction

During the last few decades, numerous possible control actions and control strategies for wastewater treatment (WWT) processes have been proposed in the scientific literature. Such strategies may have been conceived as a result of logical reasoning, modelling and simulation studies, lab-scale experiments, pilot-scale experiments, full-scale applications or different combinations of those. However, the vast majority of the suggested strategies are never thoroughly evaluated by anyone else but the authors and their co-workers, yet alone implemented in any full-scale applications and properly validated. Why is this the case? Obviously, one relevant control objective for WWT control would be to achieve sufficiently low concentrations of biodegradable matter and nutrients in the effluent water with minimal sludge production at minimum costs—a fairly simple and straightforward criterion. Would it not be beneficial to both the scientific and practical WWT communities to have an objective, unbiased and clear method to verify (at least within certain probabilities) whether or not a newly proposed control strategy is able to accomplish such a set of criteria more efficiently than other available strategies? That the above question represents a relevant research issue is the motive for a project referred to as the COST 624 benchmark simulation model. The overall goal of the work is to develop a general software tool for benchmarking, i.e. performance assessment and evaluation, of control strategies for WWT systems.

The evaluation and comparison of control strategies, either practical or based on simulation are difficult. This is partly due to the variability of the influent, to the complexity of the biological and physico-chemical phenomena and to the large range of time constants (from a few minutes to several days) inherent in the biological processes. Also complicating the evaluation is the lack of standard evaluation criteria. This is largely due to the fact that effluent requirements and treatment costs (e.g. labour and energy) are often location specific. Consequently, it is difficult to judge the particular influence of an applied control strategy from a reported performance increase, as the reference situation is often less than optimal. If a common starting-point for the processes is not defined then it becomes impossible to compare the relative differences between different strategies. Due to the complexity of the systems it is a substantial effort to develop alternative controller approaches; hence, a fair comparison of different options is rarely made. And, even if this is done, it remains difficult to conclude to what extent the solution is process, location or time specific. Simulations, on the other hand, provide a cost-effective means for the

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evaluation of control strategies, but the unlimited number of simulation permutations makes the need for a standardised protocol very important if different strategies (and different simulation results) are to be compared.

To enhance the acceptance of innovative control strategies the evaluation should be based on a rigorous methodology and standardised simulation procedure including the definition of a comprehensive simulation model of the plant, plant layout, influent load, controllers, sensors, performance criteria and test procedures. The idea to develop a tool for this specific purpose gradually evolved within the framework of the European Co-Operation in the field of Scientific and Technical research (COST) Action 682 "Integrated Wastewater Management" as well as within the first IAWQ (later IWA) Task Group on respirometry-based control of the activated sludge process. Within the later COST Action 624 on "Optimal Management of Wastewater Systems" close collaboration was established in order to develop a consistent and standardised simulation protocol. More details about the progress and development of the benchmark may be found in, for example, Spanjers, Vanrolleghem, Nguyen, Vanhooren, and Patry (1998), Alex et al. (1999), Pons, Spanjers, and Jeppsson (1999), Copp (2000a) and Pons, Jeppsson, Copp, and Spanjers (2002).

2. Current status

Based on the available features of the benchmark simulation model almost 100 scientific papers have been published world wide. The software implementations have been freely distributed to research groups on almost every continent and the basic benchmark is available as a built-in feature within several of the major commercial software packages for WWT modelling and simulation (e.g. WEST®, SIMBA®, GPS-X™). All this accomplished within a time period of only 5 years. Consequently, it is a reasonable statement that a need existed within the scientific community for the type of tool and methodology described in this paper.

The COST benchmark was originally defined as "a protocol to obtain a measure of performance of control strategies for activated sludge plants based on numerical, realistic simulations of the controlled plant". The design of control strategies should not be included in the benchmark. It was quickly decided that the official plant layout would be aimed at carbon and nitrogen removal in a series of activated sludge reactors followed by a secondary settling tank, as this is perhaps the most common layout for full-scale WWT plants today (see Fig. 1). The selected model description for the biological processes was the recognised activated sludge model no. 1 (ASM1) (Henze, Grady, Gujer, Marais, & Matsuo, 1987) and the chosen settler model was a one-dimensional 10-layer model together with the double-exponential settling velocity model proposed by Takács, Patry, and Nolasco (1991).

To allow for uniform testing and evaluation three dynamic input data files have been developed, each representing different weather conditions (dry, rain and storm events) with realistic variations of the influent flow rate and composition. These files can be downloaded from the COST Action 624 website (http://www.ensic.inpl-nancy.fr/COSTWWTP) and have been widely used by various research groups also for other purposes than actual benchmarking. To represent a true challenge for on-line control strategies, the simulated plant is a high-loaded plant with significant influent variations.

In order to apply different control strategies a number of control handles (i.e. actuators) and measurement signals (i.e. sensors) must be available. A high degree of flexibility is required, so that the implementation and evaluation of an innovative strategy is not limited. The default benchmark control strategy only use two measurement signals (dissolved oxygen and nitrate concentrations) and two control handles (air flow rate and internal recirculation flow rate). However, the benchmark simulation model allows for approximately 30 different control handles (different types of step-feed and step-recycling, external carbon source addition, etc.) and a wide variety of sensors. At this stage of development, all actuators are assumed to behave ideally whereas the sensors are divided into different classes depending on their characteristics (delay, noise, detection limit, etc.). Consequently, just about every conceivable real-time control strategy for activated sludge systems can be implemented within the framework of the COST benchmark.

A general set of criteria has been defined within the benchmark description to assess the overall performance of the applied control strategy. Two system performance levels exist: (1) process performance and (2) control loop performance. The first level of assessment quantifies the effect of the control strategy on the plant in terms of an

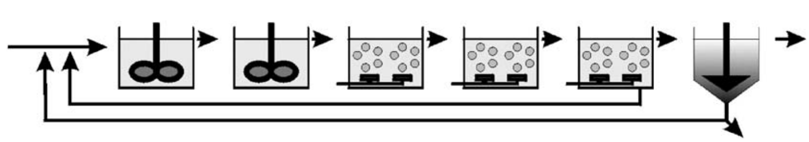

Fig. 1. Schematic representation of the COST benchmark configuration (from Copp, 2002).

effluent quality index, effluent violations (related to defined limits for the plant) and operational costs (energy for pumping and aeration as well as sludge production). The second level of assessment quantifies the effect of the control strategy on controller performance by means of different statistical criteria on the controlled and manipulated variables. This more detailed analysis makes it possible to estimate the effect of a control strategy in terms of wear and tear of actuators, controller robustness, disturbance attenuation, etc.

All details of the current benchmark are available at the associated website (COST Action 624 website) and also as a publication (Copp, 2002). A substantial effort has gone into verifying the steady state and dynamic output data included in the description. Cross-platform checking of the benchmark has successfully demonstrated its use on a number of commercially available simulation software tools. The benchmark manual (Copp, 2002) summarises the various tested implementations with helpful hints for new ''benchmarkers''. The complete manual can also be downloaded from the website. So far, results have been verified using BioWin™, EFOR™, GPS-X™, MATLAB/SIMULINK™, SIMBA®, STOAT™, WEST®, JASS and a user defined FORTRAN code.

3. Future development and perspective

An obvious drawback of the current benchmark simulation model is its limitation to the single-sludge continuous-flow activated sludge process. Although this process is commonly used a WWT plant certainly involves many other processes. Moreover, in terms of operational costs the treatment of sludge is often higher than the treatment of the water phase and therefore this part cannot be neglected. Focussing only on the activated sludge process may lead to sub-optimisation and a successful control strategy must involve all aspects of a plant. For this reason, the benchmark developers are extending the scope of the benchmark to include more processes. An enlarged plant layout has been defined, which involves primary sedimentation, sludge thickening, sludge dewatering, flow equalisation and anaerobic digestion processes. Together with the already existing parts of the benchmark this extension will allow for development and assessment of control strategies based on plant-wide rather than process-wide control. The selected model chosen to describe anaerobic digestion is the Anaerobic Digestion Model no. 1 (Batstone et al., 2002). To allow for reliable model integration of the ASM1 and ADM1 models a dynamic state variable interface has also been proposed (Copp, Jeppsson, & Rosen, 2003). In the future, other commonly used processes should be included in the benchmark, for example enhanced biological phosphorus removal, biofilm processes and sequencing batch reactors. To promote more realistic simulations it may also become necessary to include more detailed model behaviour, such as adaptation of biomass, presence and effects of toxic substances in the influent, temperature effect on biological rates and change in settleability properties related to filamentous bacteria.

A more stringent description of sensors and their behaviour is currently being evaluated to promote a more realistic test environment and allow control engineers to define the requirements of the measuring equipment as a function of the selected control strategy (Rieger et al., 2003; Alex, Rieger, Winkler, & Siegrist, 2003). The proposed sensor models are divided into six classes and include response time, noise and drift but may also be extended to describe calibration and cleaning intervals. A next step for even more realistic simulation results would be to model the response of the various actuators in terms of delays and other practical limitations. In the current implementation all actuators are considered ideal apart from a maximum limit of the actuator capacity. A future possible extension would be to include failures of sensors, actuators, data transmission equipment, etc., based on different stochastic properties of the devices.

As the number of processes available in the COST simulation benchmark model increases the need to extend the performance assessment criteria will also become apparent (e.g. methane production in an anaerobic digestion unit, energy content of dewatered sludge). However, it is essential to maintain the control strategy evaluation as simple as possible to allow for easy comparisons. A few possible extensions are already being discussed among the developers. A monetary operating cost performance index has been proposed (Vanrolleghem & Gillot, 2002), although not yet an 'official' part of the COST benchmark. Monetary assessment is difficult to implement on a general level but it cannot be neglected as it is often the most important practical aspect when deciding on new operational strategies for a WWT plant. A penalty must also be associated with the number of sensors and actuators required for a certain control strategy. Such a criterion is related to the most general rule for automatic control—*keep it simple*. Even for the existing benchmark it has not been possible to evaluate the performance of the control strategy using only one criterion. Therefore it may be beneficial (and necessary) to apply a multi-objective decision-making procedure at the end of the assessment to enhance the overall usability of the benchmark. Some proposals regarding this topic have already been suggested (Copp, 2000b; Vanrolleghem & Gillot, 2002) but more discussion and evaluation are required before such a tool can be implemented.

The future vision of the COST benchmark simulation model is a stand-alone and free software tool that any

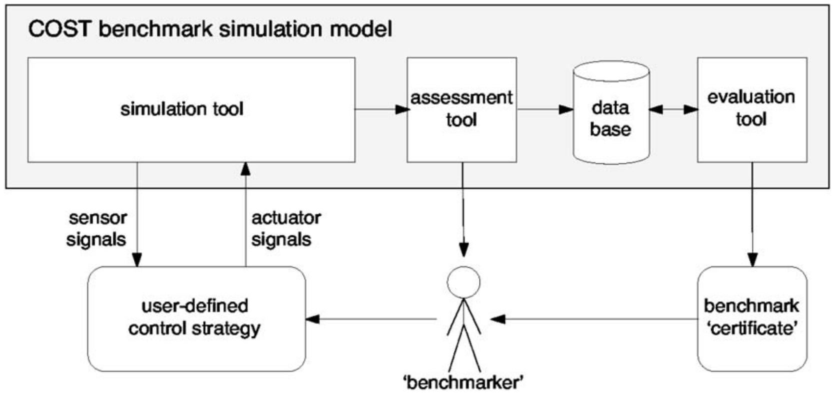

Fig. 2. Schematic description of the future COST benchmark simulation model.

user can download or simulate over the Internet using a browser. Implementations for all the verified simulation packages would be available. A first attempt of this vision is already available for the JASS simulator (Samuelsson, Ekman, & Carlsson, 2001; JASS website), which is a JAVA-based simulator where the existing benchmark model has been implemented. Using a normal browser any user can set up a variety of control strategies and investigate how the plant performs according to the defined evaluation criteria. At this stage only a number of predefined sensors and control handles are available but in the future the potential user may simply define what sensors (type, class, location) and actuators (type, class, location) are required and connect the virtual input and output signals to the control strategy under investigation. The system would then be simulated for a variety of conditions, such as different input characteristics and sensor failures, and the behaviour of the control strategy automatically assessed according to the benchmark criteria and stored in a general WWT benchmark database together with a detailed description of the tested strategy. These results would be evaluated and compared to other strategies previously stored in the database. A benchmark 'certificate' describing the proposed control strategy and its performance evaluation would finally be issued to the user, which would serve as a "quality insurance" that the proposed strategy has been properly validated and fulfils the criteria of the COST benchmark simulation model. The principle is shown in Fig. 2.

4. Introduction to the benchmark papers

In the following section of this journal six papers devoted to the COST benchmark simulation model are published. They represent a selection of papers from sessions on wastewater control, optimisation and benchmarking presented at the 15th IFAC World Congress Conference in Barcelona, in 2002. These types of papers represent highly valuable information to the COST benchmark developers. The feedback from different research groups using the benchmark and applying it to their own cases is the best way of validating the tool as well as providing information regarding the strengths and weaknesses of the system, possible extensions, etc. The benchmark developers are most grateful for their efforts.

In its present form, the COST simulation benchmark model is limited to benchmarking of the activated sludge process only. Other processes of a general WWT plant have been neglected. Obviously, this represents a significant limitation and efforts are currently being made to extend the scope of the benchmark. However, three of the following papers are describing possible ways to extend the current implementation. In the paper "Benchmarking combined biological phosphorus and nitrogen removal WWT processes" by Gernaey and Jørgensen, an effort has been made to use the Activated Sludge Model no. 2d (Henze et al., 1999) rather than ASM1. The ASM2d includes biological phosphorus removal. As a result of using this extended mathematical model the plant layout, influent wastewater characteristics and evaluation criteria also require some modifications although these are kept to a minimum in order to maintain a close relationship to the original benchmark. Based on this extended benchmark, the behaviour of two different control strategies are compared and evaluated. The paper "Benchmarking procedure for full-scale activated sludge plants" by Abusam et al. is more focussed on real-world application. A general idea of the COST benchmark is the testing of control strategies on a unified plant design in order to enhance unbiased comparisons and assessments of the results. Abusam et al. describe an approach to allow for specific plant designs and operational characteristics, while still maintaining the ability to objectively compare the performance of such different plants. The paper includes an illustrative example where a control strategy for an existing full-scale oxidation ditch plant is evaluated. In the paper "Control strategy robustness with respect to hydraulics" by Pons and Potier, the relevance of the

COST benchmark model sophistication to validate different control strategies is challenged with respect to hydraulic phenomena. It is well known that hydrodynamic effects play a major role in real-world applications but such effects are for reasons of simplicity not included in the COST benchmark model. Consequently, Pons and Potier extend the existing benchmark model with hydraulics and investigate how the performance assessment of several control strategies is affected when compared to the original benchmark. However, the conclusion is that the impact of hydrodynamics on the results is not significant enough to motivate the increased model complexity required to include these phenomena.

The paper "Simulation of respirometry-based detection and mitigation of activated sludge toxicity" by Copp and Spanjers, represents a somewhat different approach. This paper is actually related to the IWA respirometry benchmark model (Copp, Spanjers, & Vanrolleghem, 2002) rather than the COST benchmark. Although the two have been developed in close collaboration some small differences exist. The investigated control strategy deals with toxic events in an activated sludge process based on measurements of the respiration rate, which requires modifications to both the mathematical model and influent wastewater. Moreover, the plant layout is extended to include a storage tank (certainly appropriate for handling toxic events). The evaluation criteria remain almost identical to the original benchmark and care is taken to minimise the other necessary modifications. Consequently, the paper suggests a possible extension to the benchmark and also represents an assessment of a nouvelle control strategy.

The last two papers do not suggest any modifications to the existing benchmark model but instead focus on applying the COST benchmark as a tool to evaluate new control strategies. In the paper "Multicriteria control strategy for cost/quality compromise in WWT plants" by Cadet et al. a reduced model suited for model-based control is developed and tested and two new control algorithms applied—an L/A control law and an adaptive non-linear linearising control law. The new control algorithms produce better effluent quality than the default benchmark control principle but at a higher cost. To overcome this problem a multicriteria control strategy for cost/quality trade-off is added on top of the other controllers, allowing a switch between the control laws depending on the current situation and priorities. The switching is realised by fuzzy logic and demonstrates good results. The paper "Comparison of advanced control strategies for improving the monitoring of activated sludge processes" by Zarrad et al. describes and evaluates three different control strategies within the 'restrictions' of the COST benchmark. Special emphasis is put on maintaining the stability of the closed-loop process in the presence of external disturbances as well as the estimation of unknown input variables for diagnostic purposes. The first strategy is based on two independently optimised PI controllers whereas the other two involves system identification and a consequent state-space description of the process to control. From a state-space model a linear quadratic controller is designed as well as a disturbance accommodating controller. All strategies are evaluated by the performance criteria of the benchmark and conclusions are drawn.

5. Conclusions

The rapid success of the COST benchmark simulation model demonstrates the scientific need for objective comparisons of new and innovative control strategies for WWT processes. Without such a tool the results and conclusions from many proposed strategies will remain unchallenged and frequently remain an academic product rather than a potential solution to actual important problems. Traditionally, presented results are often troublesome to compare as they have been achieved using different mathematical models, different plant configurations, a variety of influent wastewater characteristics, etc. It is consequently often impossible to determine whether the presented results are primarily due to local factors or if the control strategy is generally applicable and beneficial.

The developers of the COST benchmark have chosen to begin with one of the most common type of WWT plants—a continuous flow activated sludge plant performing nitrification and predenitrification. The ongoing extensions include several commonly used processes (anaerobic digestion, primary settling, thickening, dewatering, etc.) as well as more comprehensive ways of describing the features of different sensors and actuators (e.g. delays, noise, failures). Moreover, it has not been possible to evaluate the performance of a control strategy using one criterion and therefore a multi-objective decision making procedure should be further developed and applied to the benchmark simulation model.

The future vision of the benchmark is a stand-alone and free software tool that any user can download. The potential user will define what sensors and actuators are required and connect the virtual input and output signals to the control strategy under investigation. The system is then simulated for a variety of conditions, such as different input characteristics and sensor failures, and the behaviour of the control strategy automatically evaluated and compared to other strategies gathered in a general WWT benchmark database. A benchmark 'certificate' describing the proposed control strategy and its performance evaluation is finally issued to the user, which serves as a "quality insurance" that the proposed strategy has been properly validated and fulfils the criteria of the COST benchmark simulation model.

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