Extension of the IWA/COST simulation benchmark to include expert reasoning for system performance evaluation

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Abstract In this paper the development of an extension module to the IWA/COST simulation benchmark to include expert reasoning is presented. This module enables the detection of suitable conditions for the development of settling problems of biological origin (filamentous bulking, foaming and rising sludge) when applying activated sludge control strategies to the simulation benchmark. Firstly, a flow diagram is proposed for each settling problem, and secondly, the outcome of its application is shown. Results of the benchmark for two evaluated control strategies illustrate that, once applied to the simulation outputs, this module provides supplementary criteria for plant performance assessment. Therefore, simulated control strategies can be evaluated in a more realistic framework, and results can be recognised as more realistic and satisfactory from the point of view of operators and real facilities.

Keywords Activated sludge; expert system; filamentous bulking; foaming; IWA/COST benchmark; rising sludge; settling problems

Introduction

The IWA/COST simulation benchmark has often been used by the wastewater research community as a standardised simulation protocol to evaluate and compare different control strategies for a biological nitrogen removal process. It includes a plant layout, simulation models and parameters, a detailed description of the influent disturbances (dry weather, storm and rain events), as well as performance evaluation criteria to determine the relative effectiveness of proposed control strategies (Copp, 2002).

Several applications of the IWA/COST simulation benchmark can be found in literature demonstrating the performance of different control strategies when tackling the influent disturbances (Vrecko *et al.*, 2002; Zarrad *et al.*, 2004). Recently, some studies have expanded the benchmark for other plant configurations (Abusam *et al.*, 2004; Pons and Potier, 2004) or have included biological phosphorus removal processes (Gernaey and Jørgensen, 2004). Moreover, some studies apply the benchmark to investigate the effects of toxic influent shock loads by introducing new state variables that modify the heterotrophic growth and decay rates (Copp and Spanjers, 2004). Summarising, any effect that can be described (and thus simulated) by the activated sludge models (ASM), can be compared and evaluated using the performance indices developed.

However, it is well recognised that the activated sludge process constitutes a complex system, consisting of a multi-specific microorganism population that often evolves to imbalances causing severe operational problems. It is also commonly reported that biological nutrient removal processes, in which environmental conditions are continuously alternating between aerobic, anoxic and anaerobic, favour the growth of various filamentous microorganisms which compete with floc-forming organisms (Martins *et al.*, 2004a).

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The absence of basic knowledge about the interaction mechanisms between the micro-organism communities and operational parameters, which are not described by standard models, is an obvious limitation when evaluating control strategies via simulations. For example, although there are several hypotheses to explain the development of filamentous bacteria, none of them provide a definitive and general solution. Moreover, most of these theories still lack experimental verification (Martins *et al.*, 2004b). Therefore, heuristic knowledge, qualitative information and operator expertise are still necessary components when dealing with these operational problems in real wastewater treatment plants (WWTP).

Operational problems whose origin is caused by imbalances between the microorganism populations in the activated sludge (Wanner, 1998; Jenkins *et al.*, 2003) or undesirable operating conditions, such as rising sludge in the secondary settlers (Henze *et al.*, 1993), are beyond the scope of the current IWA/COST simulation benchmark. The benchmark is solely based on numerical control algorithms and standard mechanistic activated sludge process models. Therefore, optimising WWTP control performance within the simulation benchmark may, for example, drive the system to a situation with maximum process performance and minimal energy consumptions, but with operational parameters that could be recognised by WWTP experts as unrealistic and potentially leading to operational problems. An example is a significant decrease of the waste activated sludge flow rate over a long period of time. This situation would certainly lead to practical problems in real plants, e.g. very high sludge residence time or too low food-to-microorganism ratio. As a result, the sludge quality deterioration attained would drive the plant to conditions favourable for severe operational problems (e.g. increasing the risk of bulking or harness the appearance of biological foams) (Jenkins *et al.*, 2003). Furthermore, remedial action to manage these problems could lead to increased operating costs.

In this context, the authors propose an extension of the current simulation benchmark by integrating an expert reasoning module in the evaluation step that infers potential operational problems in the activated sludge process from the simulation outputs. This module, composed of knowledge-based flow diagrams, explores influent and effluent compositions and operating conditions at each time interval, to detect favouring conditions for filamentous bulking, foaming and rising sludge problems. These diagrams were developed based on knowledge acquired from literature and the authors' expertise in this field. Once codified, the module can be integrated as an independent tool within the existing benchmark and provide new performance criteria that offer advice concerning the potential risk that the evaluated control strategy may bring about operational problems in the activated sludge process.

The purpose of this paper is to present and demonstrate the capabilities of a new expert reasoning module in order to alert a user of possible settling problems during the evaluation of control strategies through the simulation benchmark. The paper details the development of this extension of the IWA/COST benchmark to include expert reasoning, and then illustrates the performance of this module with a number of simulated case studies. The performance of this module is evaluated using the weather disturbances as influent data.

IWA/COST simulation benchmark

The original IWA/COST simulation benchmark is used in this work (Copp, 2002). The benchmark plant layout consists of five completely mixed reactors with a total volume of 5,999 m^3 including a pre-denitrification section which occupies 1/3 of this volume. The ASM1 (Henze *et al.*, 1987) was selected to model the biological processes while the Takács ten-layer model (Takács *et al.*, 1991) was chosen to describe the settling processes. Oxygen transfer coefficient of the last aerated tank, internal recycle flow rate, return activated sludge (RAS) flow rate and waste activated sludge (WAS) flow rate are the four manipulated variables of the benchmark plant. Nevertheless, only the first two variables are actively used by the default benchmark control strategy, to control the dissolved oxygen (DO) level in the third aerated reactor and the nitrate concentration in the second anoxic reactor, respectively. All simulations and performance assessments were carried out using the MATLAB 6.5/SIMULINK 5.0 (Mathworks, Inc.) implementation of the IWA/COST simulation benchmark and performed as specified in the Benchmark protocol (Copp, 2002).

Expert module development

The flow diagrams

There are different ways to diagnose filamentous bulking, foaming or rising sludge. In full-scale plants, the most common approaches involve visual observation of floc appearance, sludge settleability and status of the biological reactor or secondary settler (presence of foam, release of bubbles, etc.). Another way to detect these problems (or at least the risk of their appearance) is by means of performing microbiological observations and by identifying specific strains of filamentous bacteria by using the fluorescent *in situ* hybridization (FISH) technique. It is well recognized that a massive presence of specific filamentous bacteria is a good indicator of an imbalance between microbiological communities and the beginning of solids separation problems. Volume fractions of 1–20% of extended filamentous bacteria in the activated sludge culture are sufficient to cause bulking sludge (Martins *et al.*, 2004b). Several authors have proposed different knowledge-based decision trees and flow diagrams to represent the reasoning procedures to identify the presence of such operational problems (Patry and Chapman, 1989; Chan and Koe, 1991; Comas *et al.*, 2003; Poch *et al.*, 2004).

Literature provides several equations and charts that allow estimating the risk of operational problems from process data which are seldom measured in real WWTPs (readily biodegradable substrate, S_S) or are only available with some delay (BOD_5), although these variables are considered by most mechanistic models. Therefore, such correlations cannot be applied to real facilities but can be easily simulated.

In line with the simulation benchmark, the knowledge-based flow diagrams proposed here only use the data available in the simulated output file. Hence, these diagrams make use of concentrations of state variables at any point of the benchmark plant (e.g. S_S or BOD_5), operational parameters such as the WAS flow rate or the RAS flow rate, and calculated parameters such as food-to-microorganism (F/M) ratio or sludge residence time (SRT).

A review of the existing knowledge regarding these problems, combined with the authors expertise, have enabled the construction of one flow diagram for sludge filamentous bulking, one for foaming and one for rising sludge (Henze *et al.*, 1993; Wanner, 1994; Grady *et al.*, 1999; Jenkins *et al.*, 2003).

Filamentous bulking. Three main branches can be distinguished in the flow diagram for identifying filamentous bulking conditions (Figure 1). Each branch is focused on one of the main causes of filamentous bulking (Jenkins *et al.*, 2003): low dissolved oxygen concentration (left), nutrient deficiency (middle) and low F/M ratio or substrate limiting conditions (right). Filamentous bulking sludge caused by septic conditions or low pH in the influent cannot be considered within the current benchmark model. The left branch of the tree illustrates that limiting DO conditions in the biological reactors relies on the current F/M ratio (Grady *et al.*, 1999). Encouraging conditions for the growth of low F/M

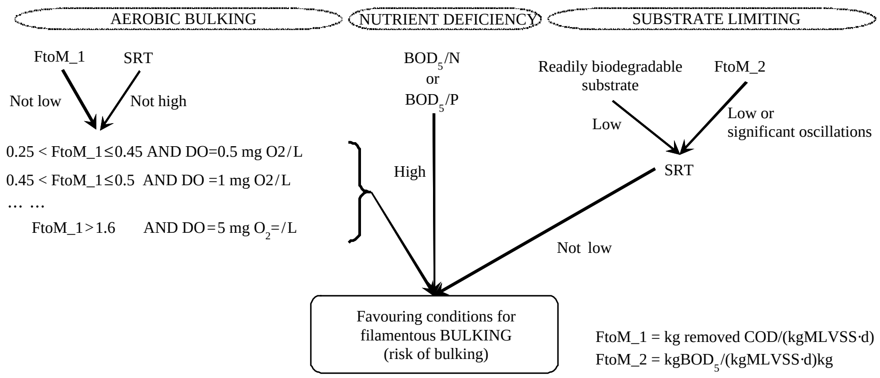

Figure 1 Flow diagram developed to evaluate the risk of filamentous bulking

filamentous bacteria can be caused by both readily biodegradable substrate limiting conditions in the bioreactor and by low influent organic loading. If the simulation results indicate that conditions for more than one branch are completely fulfilled, the worst conditions are selected.

Foaming. This flow diagram has two main branches which allow investigation of the existence of operational conditions that lead to foaming problems (Figure 2). The left branch looks for the environmental conditions enhancing the growth of Nocardioforms filamentous bacteria and *Microthix parvicella*, the most common filamentous microorganisms causing foaming (Jenkins *et al.*, 2003). These species are favoured, compared to the floc forming bacteria, when the plant experiences low F/M ratio and high SRT in combination with low DO concentrations, in the case of *M. parvicella*, which also causes sludge bulking. Although less frequently, type 1863 can also form biological foams if the influent contains a high fraction of readily biodegradable organic matter (RBOM fraction).

Rising sludge. Rising sludge is primarily a problem if the nitrate concentration in the secondary clarifier influent is higher than 8 mg $N\text{-}NO_3{\cdot}L^{-1}$ (critical nitrate concentration according to Henze *et al.*, 1993). In this situation, favourable conditions for rising sludge

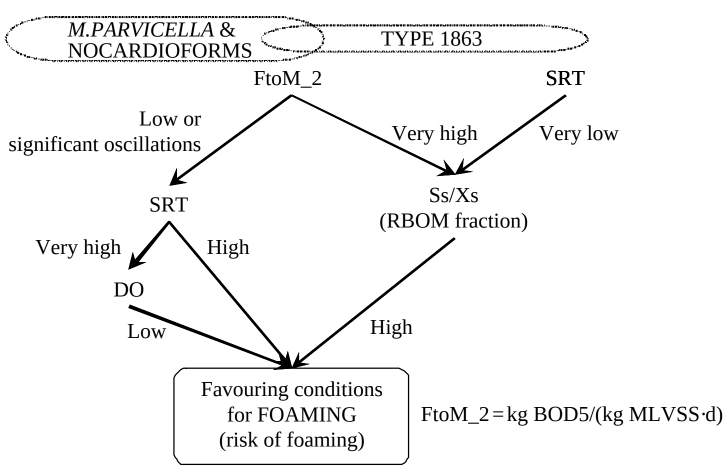

Figure 2 Flow diagram developed to evaluate the risk of foaming

are identified by the development time of nitrogen gas bubbles (time needed to remove the oxygen plus time required for denitrifying the critical nitrate concentration). If the nitrogen gas production time is lower than the sludge residence time in the secondary settler, then rising sludge due to denitrification in the secondary settler is probable. The sludge residence time in the settler is computed as the volume of settling sludge divided by the RAS flow rate. Fast DO consumption is assumed in the settler and therefore the denitrification rate is always computed assuming no oxygen inhibition ($DO = 0\,mg\ O_2 \cdot L^{-1}$).

A fuzzy implementation

Traditionally, any flow diagram or decision tree can be converted to production rules by traversing each branch from the root to the leaves and codifying it as an IF-THEN rule set. The collection of rules extracted from the previous flow diagrams constitutes the knowledge base of the expert reasoning module. These rules, together with some required variables, were implemented as a script in MATLAB 6.5 (Mathworks, Inc.).

The uncertainty and subjectivity associated with the description of heuristic knowledge are features common to any domain involving expert knowledge. There are several approaches to cope with this ambiguity. In this work, uncertainty is tackled using the principles of fuzzy decision theory (Bellmann and Zadeh, 1970). By using fuzzy logic, the uncertainty of a proposition can be represented by the degree of truthfulness or falsehood to which it is a member of a certain fuzzy set, and be quantified by certain qualifiers such as low, normal, medium or high. Therefore, the limitation of using rules with crisp confines, which are based on bivalent Boolean logic, is avoided. Hence, with fuzzy truth values, this module will provide, for example, the extent to which the risk of filamentous bulking arises in the process instead of saying unequivocally whether the risk of filamentous bulking is true or false. This is called the degree of membership, also known as possibility, in the set or class "risk of filamentous bulking", with a membership value between 0 and 1.

The MATLAB 6.5 fuzzy toolbox was used to develop the membership functions and rule bases for each flow diagram. Fuzzy sets and membership functions were defined by F/M_1 ratio, F/M_2 ratio, SRT, DO, BOD_5/N ratio, readily biodegradable substrate (S_S), S_S to slowly biodegradable substrate (X_S) fraction, "risk of filamentous bulking", "risk of foaming" and "risk of rising sludge". The limits for each fuzzy membership set were stated according to the values in the existing specialised literature even though users can calibrate these ranges as well as their degree of overlap. In total, approximately 120 IF-THEN rules, designed according to the expert flow diagrams, conform the fuzzy knowledge base or decision matrix of the expert module.

The application of the new expert module to the simulation outputs allows a degree of truthfulness to be obtained regarding the risk of filamentous bulking, foaming and/or rising sludge at each time step during the final 7 days of the benchmark weather file simulations. These *alarms* constitute new performance criteria about settling problems (the *Settling Quality Criteria*), which complement the existing performance indices for comparing the impact of different control strategies.

Similar to the existing plant performance evaluation criteria, results from the new module are reported in three different ways for each of the settling problems: (i) a time series plot showing the risk of settling problems occurrence from the 7th to the 14th day; (ii) the percentage of time during which the plant is experiencing severe risk of settling problems (a modifiable limit value of risk = 0.8 was adopted for defining a severe problem); and, (iii) the most dangerous situation during the evaluation period, computed as the largest time interval the plant is exposed to an uninterrupted severe risk of a settling problem.

Since it has been implemented as an independent m-file, the expert reasoning module can either be launched independently or as a part of the traditional benchmark performance evaluation criteria.

Simulation results

In order to demonstrate the performance of the proposed module, two different control strategies were tested and compared in this study: the default control strategy and control strategy-2 (same as the default one but with a RAS flow rate proportional to the influent flow rate with a gain of 2). The new expert module was applied to the benchmark simulation outputs of both control strategies. The time series plots, providing the risk of potential settling problems for both control approaches, are shown in Figures 3 and 4. These figures illustrate the last 7 days of simulations using the rain weather influent data as input disturbance.

From the figures, it is seen that different control strategies can direct the process towards different settling problems. The figures illustrate that, while there is not much difference in the case of aerobic bulking, the operational conditions caused by control strategy-2 lead to a high risk of both low F/M filamentous bulking and low F/M foaming. For both problems, the higher RAS flow rate of strategy-2 causes underloading of the sludge in the bioreactors, since it leads to higher biomass concentrations in the activated sludge tanks, and thus a higher SRT. On the other hand, this control strategy reduces, on

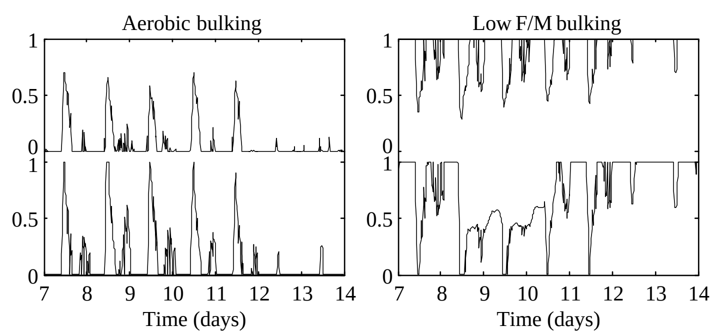

Figure 3 Risk of aerobic and low F/M bulking under rainy influent conditions (top: strategy-2; bottom: default)

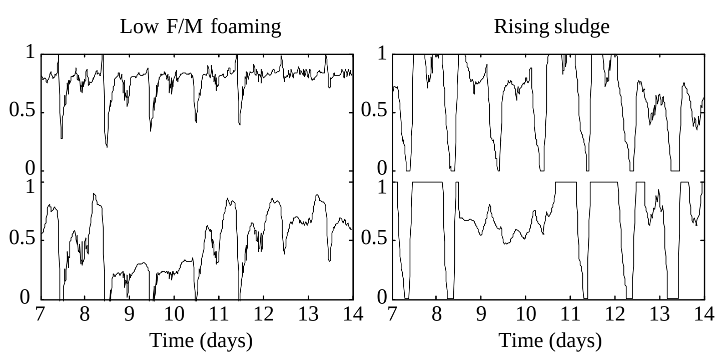

Figure 4 Risk of low F/M foaming and rising sludge under rainy influent conditions (top: strategy-2; bottom: default)

Table 1 Plant performance obtained using two different control strategies under different influent conditions

Performance criterion	Dry influent		Rain influent		Storm influent	
Operating cost index (€/year)	796724[1]	768911[2]	885047[1]	861182[2]	859600[1]	834092[2]
Effluent quality (kg·d^{-1})	7556	7193	9038	8717	8304	7952
Sludge production (kg·d^{-1})	2441	2244	2358	2111	2606	2372
Aeration energy (kWh·d^{-1})	7241	7208	7170	7236	7286	7287
Pumping energy (kWh·d^{-1})	1488	1623	1927	2095	1727	1945
No. of TN viol./% t viol.	7/18.3	4/3.9	5/11.3	1/1.3	7/15.8	3/3.4
No. of S_{NH} viol./% t	5/17.3	4/3.6	8/26.8	5/6.7	7/26.8	4/ 4.9
No. of TSS viol./% t	0/0	0/0	0/0	1/0.3	2/0.3	2/3.6
Settling quality criteria						
% t DO bulking	1.8	0	3.6	0	3.3	1.0
Worst situation (d)	0.1	–	0.1	–	0.1	0.1
% t F/M bulking	68.8	81.3	50.9	76.3	62.9	80.2
Worst situation (d)	0.9	1.0	0.9	1.0	0.9	1.5
% t F/M foaming	14.9	56.8	13.1	70.8	8.3	43.5
Worst situation (d)	0.2	0.4	0.3	0.6	0.2	0.3
% t rising	64.0	44.5	39.6	30.1	56.9	43.5
Worst situation (d)	0.7	0.7	0.7	0.3	0.7	0.5

[1]Default control strategy; [2]Control strategy-2

average, the risk of rising sludge by 26% because the SRT in the secondary clarifier is decreased. Filamentous bulking risk due to nitrogen deficiency is never high because the N load into the plant is high throughout the simulation. A high risk of foaming due to a high easily biodegradable organic matter fraction is never detected because a situation with high concentration of easily biodegradable substrate is never encountered in the benchmark weather files. In order to enhance interpretation of the results, a suitable filter will be designed and applied to the expert module results. This filter, which can be different depending on the problem dynamics, will then elucidate these episodes where the risk for the occurrence of a selected problem is continuously high during a specific period of time.

The plant performance was also evaluated for all influent conditions in relation to not only the former criteria defined by the benchmark and the operating cost index (Vanrolleghem and Gillot, 2002), but now also in relation to the settling quality criteria described in the previous section. Values of these criteria for both selected control strategies are shown in Table 1.

From the results presented in Table 1, it can be affirmed that control strategy-2 provides a lower operating cost index (without considering the settling problems!) compared with the default strategy under all weather conditions. In addition, sludge production is reduced, as are the number of violations of total nitrogen and ammonia concentrations, improving the effluent quality. However, with the new proposed criteria, the benchmark user can additionally take into consideration the risk of filamentous bulking, foaming and/or rising sludge, when applying a given control strategy.

Conclusions and future perspectives

A new expert reasoning module that complements the evaluation criteria of the existing IWA/COST simulation benchmark was presented in this paper. It was obtained by codifying a set of heuristic flow diagrams, which allow favourable operational conditions for microbiologically related activated sludge solids separation problems to be identified. The diagrams presented here represent a first proposal, to be refined in the future based on necessary research community consensus. The aim of these diagrams is not to diagnose settling problems with absolute certainty, but to quantify whether the evaluated control strategies could direct the process to the conditions for them to arise or not. With this new approach, the benchmark user cannot only evaluate different control strategies based on process removal efficiencies, sludge production, aeration and pumping energy, and controller performance, but also consider the propensity of microbiologically related solids separation problems that numerical models cannot describe. Therefore, control strategies can be evaluated in a more realistic framework, and the results recognised as more realistic and satisfactory from the point of view of operators and real facilities. In our opinion, this new approach, integrating the current benchmark with knowledge-based reasoning, could be a suitable framework for evaluating these complex operational problems. Topics for further research entail: extending this module to embrace other settling problems (disperse growth, non-filamentous bulking and pin-point floc) and biological nutrient removal processes; filtering the expert module results; integrating the operational problems within a total cost index; translating parts of these diagrams into simplified models; and, using the settling quality criteria as feedback to adapt the evaluated control strategy and restore the process back to normal operational conditions.

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