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Evaluation of nitrogen treatment in the wastewater treatment plant by dynamic optimization

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Abstract: This article studies the efficiency of wastewater treatment by two different methods of biological treatment based on two plants. The Benchmark wastewater treatment plant (WWTP) has two first anoxic tanks for organic treatment and denitrification; next three aerobic tanks are used for organic and nitrification treatment; nitrates from the last aerobic tank are circulated to the first anoxic tank to continue the denitrification. The Verulam WWTP is comprised of an anoxic tank for treating organic material, the next two aerobic tanks for nitrification, the fourth anoxic tank for denitrification and, finally, the aerobic one for organic matter settling. Thus, both WWTPs have two anoxic tanks and three aerobic tanks but the arrangement of tanks is different. While considering the cost of the aeration system, our research results indicate that the Benchmark WWTP is about 15% more effective compared to the Verulam one. Besides, the Benchmark WWTP is easy to control the effluent by internal recycling.

Keywords: Benchmark WWTP, Verulam WWTP, wastewater treatment, methods of denitrification, optimization.

通过动态优化评估废水处理厂中的氮处理

摘要：本文研究了基于两种植物的两种不同生物处理方法的废水处理效率。基准废水处理厂（WWTP）拥有两个用于有机处理和反硝化的第一个缺氧池。接下来的三个好氧池用于有机和硝化处理。来自最后一个好氧池的硝酸盐循环到第一个缺氧池，以继续进行反硝化。Verulam 污水处理厂包括一个用于处理有机材料的缺氧池，接下来的两个用于硝化的好氧池，第四个用于反硝化的缺氧池以及最后一个用于沉降有机物的好氧池。因此，两个污水处理厂都有两个缺氧池和三个需氧池，但是池的布置不同。在考虑曝气系统成本的同时，我们的研究结果表明，基准污水处理厂的效率比 Verulam 污水处理厂高 15％。此外，基准测试 WWTP 易于通过内部回收来控制废水。.

关键词：基准测试 污水处理厂，维拉姆污水处理厂，废水处理，反硝化方法，优化。

Introduction

Today the use of modeling to describe the treatment of organic matter and nitrogen in wastewater is quite common, typically models such as ASM1, ASM2 developed by Henze et al. [1; 2], ASM3 developed by Gujer et al. [3], ASM2d developed by Henze et al. [4], BSM1 developed by Alex et al. [5] depending on the characteristics of wastewater.

WWTP simulation and optimization were applied to consider the wastewater treatment efficiency, which has not been extensively investigated. Few works have been devoted to the dynamic optimization of these plants recently. Most of them were carried out to find out the operation ways to have high treatment efficiency. Optimal design and operation of activated sludge processes were studied in [6], this paper provided WWTP state-of-the-art review, not considering the wastewater treatment method. A WWTP model was presented in [7], as a tool to

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optimize plant operation. A dynamic simulator sewage treatment operation analysis over time (STOAT) was used under certain influent conditions to optimize design possibilities for modifying an existing primary WWTP [8], the proposed optimization was based on the concentration of total suspended solids (TSS) and biochemical oxygen demand (BOD) characteristics in the effluent, rather than taking into account all pollutants in wastewater. A long-term model of a large WWTP was set-up, calibrated and validated in [9], the optimum solid retention time of a WWTP was found using a modeling approach for two different seasons, which minimizes operating costs. A multi-step simulation-based methodology was described in [10], based on evaluation and optimization of the energy consumption at the largest Italian WWTP using limited, preliminary energy audit data, not providing measurement data. WWTP simulation and optimization were presented in [11; 12] with measurement data based on traditional wastewater treatment, without comparing the wastewater treatment methods.

The studies of the authors mentioned above only simulate and optimize models for certain WWTPs, the purpose is to save investment and operation costs as well as satisfy the wastewater discharge regulations. There have been no studies comparing wastewater treatment methods based on simulation and optimization to propose appropriate wastewater treatment methods. Therefore, this research deals with two typical wastewater treatment methods described below.

To link model theory and practice, Benchmark WWTP (Figure 1) is used to form the BSM1 model based on the ASM1 model to describe further sludge age, energy consumption and pumps in the system, and effluent quality [5]. This research was undertaken in Europe by Working Groups of COST Action 682 and 624 [13]. Now this development work continues under the umbrella of the IWA Task Group on Benchmarking of Control Strategies for WWTPs. The data of this WWTP were measured quite thoroughly (every 15 minutes); therefore, this model describes quite fully and accurately the WWTP behavior. The measurement results are given in [14].

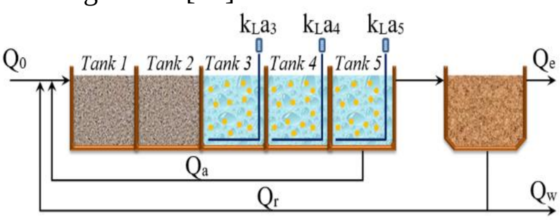


Fig.1 Configuration of the Benchmark plant

Figure 2 shows the Verulam WWTP located near Durban in South Africa [15], which is simulated by the WEST software package [16].

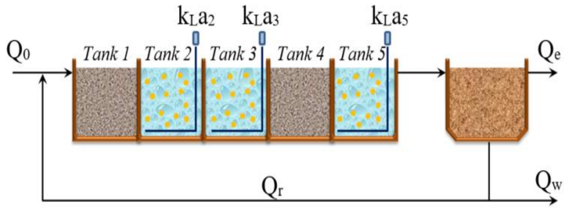


Fig.2 Configuration of the Verulam WWTP

In terms of scale and form of these two WWTPs, they are quite similar (there are five biological tanks including two anoxic tanks and three aerobic tanks), these plants differ only in the arrangement of tanks for nitrogen treatment:

- in the Benchmark WWTP nitrification is carried out in the aerobic tanks, then wastewater is pumped them to the anoxic tanks placed at the top for denitrification.

- in the Verulam WWTP nitrification is performed in the 2nd and 3rd aerobic tanks, and then wastewater is transferred to the anoxic tank 4 for denitrification, and the aerobic treatment process continues in tank 5.

Because both of these WWTPs have the same number of biological tanks, but differ in the arrangement of aerobic and anoxic tanks, we want to simulate and optimize the operation for both WWTPs to determine the treatment method which makes the process more efficient and costs less to operate. The Verulam WWTP was used for this study with the measurement data provided in [16].

No studies have compared the effectiveness of these two methods after optimization of the treatment process. The purpose of this research is to address this issue using similar WWTPs that differ only in the nitrogen treatment process by changing the function of each tank in the treatment system. Relevant results allow for consideration and selection of the most effective wastewater treatment method for daily life.

The gProms [17] was employed in this research; this is a standalone toolbox capable of performing large-scale simulation and optimization of complex processes. Its features include solving systems of DAEs, automatic root-finding of switching functions in case of hybrid model for the considered process, and automatic parametric sensitivity equations generation and evaluation, which proves to be very useful for process optimization. Nowadays, gProms representative offices are located in some developed countries to control technology in the automatic manufacturing industry. Some authors used gProms for WWTP simulation and optimization [18]; it was recognized as a quick calculation tool, and the results are very accurate.

The optimization process was performed for this research. The optimization methods may be divided into two groups, sequential and simultaneous ones [19]. Simultaneous methods are based on the complete discretization of state and control variables. As a rule, orthogonal collocation is used, and the resulting nonlinear programming problem (NLP) is solved by a gradient-based method. In the sequential processes, the control vector parameterization (CVP) is the most common approach. It involves approximation of the control variables through simple functions (e.g., piecewise constant functions) within a specified number of time intervals with equal or non-equal length. The state variables are not approximated. The resulting optimization problem is an NLP problem that is solved by a gradient-based method. The gradients of the performance index and constraints concerning the control parameters may be computed using finite differences, adjoint system or sensitivity methods. The finite differences method is computational time consuming, the adjoint system method is suitable for large size optimization problems with a reasonable number of constraints, whereas the sensitivity method is appropriate for practical size optimization problems where many restrictions are involved.

1 Research methodology

The authors simulated the Benchmark and Verulam WWTPs based on the mathematical formulas of Model ASM1 to know whether the pollution concentrations of the wastewater satisfy the discharge requirements, and at the same time determine the energy consumption of the aeration supply system. Then these two WWTPs were optimized to assess the appropriate aeration policy and circulating sludge amount to satisfy the discharge conditions and save the operating costs for the WWTP.

1.1 Configuration of WWTP s

1.1.1 The Benchmark WWTP

The Benchmark WWTP (Figure 1) consists of a reactor with five compartments for activated sludge: the first two are anoxic tanks, followed by three aerobic tanks.

The wastewater undergoes first anoxic treatment (tank 1 and 2) biologically in free cultures according to which, in a first step, the organic carbon is practically eliminated by heterotrophic bacteria. The effluent leaving the first stage is subjected to the aerobic biological treatment in free cultures for the ammonium transformation and then separated from the purified liquid in the settler. Most of the thickened sludge (several microorganisms or activated sludge) is recycled to the first tank to mix with the incident wastewater. Only a small portion is removed from the system. On the other hand, the mixed liquor from the downstream aeration tank is also recycled to the first tank (anoxic tank) for denitrification. Thus, incident wastewater directly provides the assimilable carbon required for the denitrification process, and internal recycling ensures the nitrate amount.

The structure of this WWTP includes a biological reactor with five active sludge tanks: the first two tanks operate under an anaerobic mode (with volume per tank 1000m^3), the next three tanks are aerobic (with volume of each tank being 1333m^3). The total volume of the biological tank is 6000m^3. The last one is a secondary settler with an area of 1500m^2, and a height of 4m.

1.1.2 The Verulam WWTP

The WWTP to be studied (Figure 2) is a combination of a reactor with five biological tanks and a secondary settler.

The WWTP has five equal biological tanks, the capacity of each tank is 1764m^3. The first and fourth tanks are anoxic tanks, the remaining tanks are aerobic. The secondary settler has a surface area of 692.8m^2, a height of 3m; it is used to separate sludge after the wastewater decomposition in the biological tanks. The input flow is Q_0 (5607 m^{3}d^{-1}), the effluent flow is Q_e (5487 m^{3}d^{-1}). The sediment circulating back to the first anoxic tank with Q_r (5607 m^{3}d^{-1}), part of Q_w (120 m^{3}d^{-1}) is discharged.

Experimental data were measured for three years, from 2008 to 2011 [16]. We used these same data for the two WWTPs, to optimize the aeration energy and compare the performance between them.

1.2 Process Modeling

The reactor has five tanks. The general equations for the material balance in the reactor are written as follows [5]:

- k = 1 (Tank 1):

$$\frac{dZ_1}{dt} = \frac{1}{V_1}\left(Q_a Z_a + Q_r Z_r + Q_0 Z_0 + r_1 Z_1 - Q_1 Z_1\right)$$

$$Q_1 = Q_a + Q_r + Q_0$$

- k = 2 to 5 (Tank 2 to Tank 5):

$$\frac{dZ_k}{dt} = \frac{1}{V_k}\left(Q_{k-1} Z_{k-1} + r_k V_k - Q_k Z_k\right)$$

$$Q_k = Q_{k-1}$$

Where:

Q_0 , Z_0 : influent flow rate and concentration;

Q_1 , Z_1: flow rate and concentration in tank 1;

Q_k , Z_k : flow rate and concentration in tank k;

Q_a , Z_a : internal recycle flow rate and concentration;

Q_r , Z_r : external recycle flow rate and concentration;

V_1 : volume of tank 1;

V_k : volume of tank k;

$S_{O,k}$: dissolved oxygen of tank k;

S_O^{sat} : oxygen saturation constant, equaling 8 g.m^{-3};

K_La_k : oxygen transfer coefficient of tank k;

r_k : observed conversion rate of tank k.

1.3 Optimization problem

The expression of the energy consumption by the aeration reactor is provided in [5]. The optimization problem is defined by:

- the Benchmark WWTP:

$$\underset{k_L a_i(t), Q_a}{Min}\left\{\frac{S_O^{sat}}{T\cdot 1.8\cdot 1000}\int_{t_1}^{t_2}\sum_i V_i\cdot k_L a_i(t)\,dt\right\}$$

where: i = 3, 4, 5.

- The Verulam WWTP:

$$\underset{k_L a_i(t)}{Min}\left\{\frac{S_O^{sat}}{T\cdot 1.8\cdot 1000}\int_{t_1}^{t_2}\sum_i V_i\cdot k_L a_i(t)\,dt\right\}$$

where: i = 2, 3, 5.

Subject to: $COD_e \le COD_{max}$; $BOD_{5e} \le BOD_{5max}$; $TN_e \le TN_{max}$; $TSS_e \le TSS_{max}$; $k_L a_i \le k_L a_{max}$.

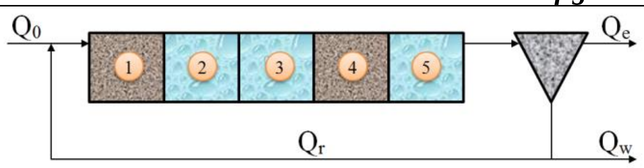
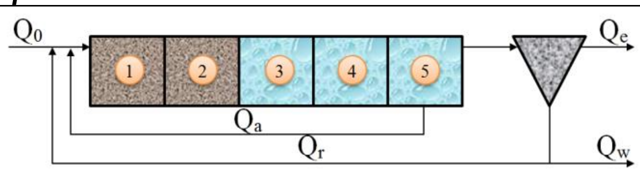
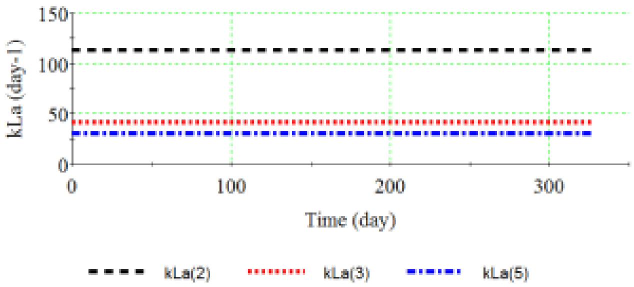
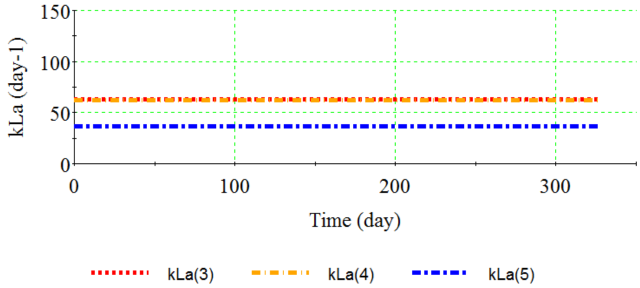
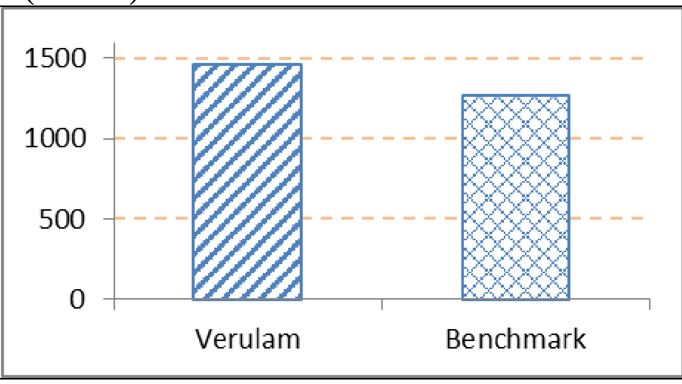
The values of the stress limits are provided in [5].

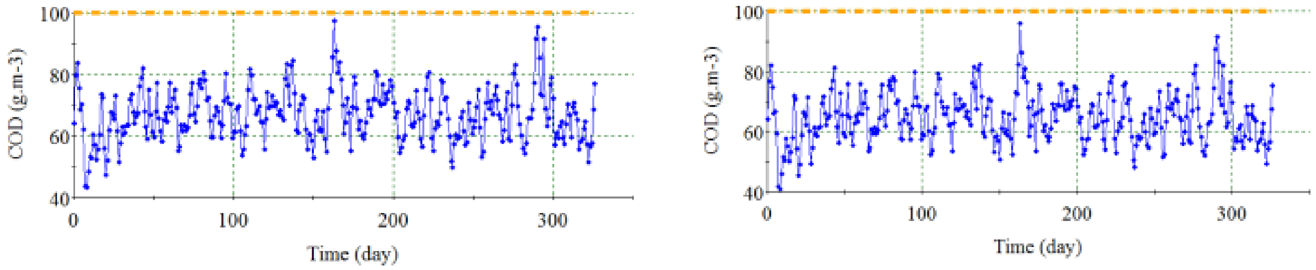
2 Results

The results of the aeration energy optimization for two WWTPs are given in Table 1. We identified a more reasonable aeration policy and sludge recirculation parameters for WWTP, so that the pollutant concentrations would meet the discharge standards, while saving operating costs, especially the cost of the aeration policy system.

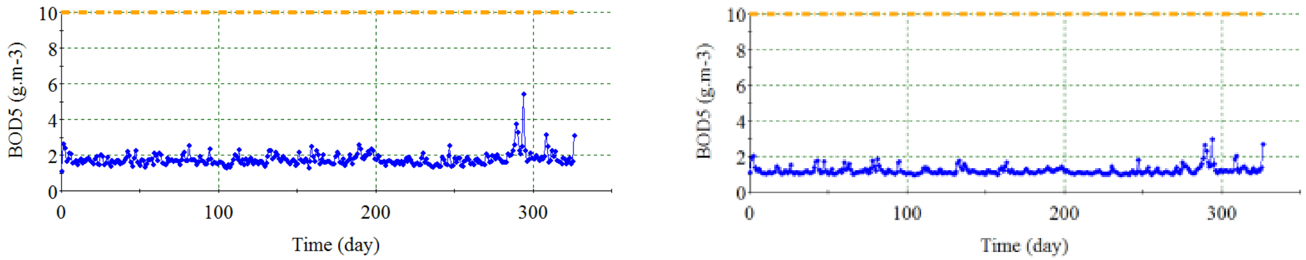
In this study, we used gProms [17] for programming based on model AMS1 [1] to simulate and optimize the WWTP.

Table 1 Three-line representation
Tab.1

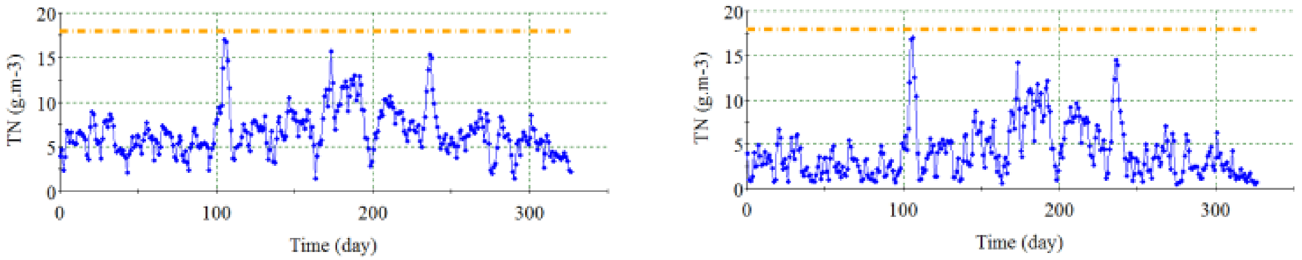
VERULAM	BENCHMARK
Configuration of WWTPs	
	
Aeration policy	
	
(k_La_2=113 d^{-1}; k_La_3=42 d^{-1}; k_La_5=31 d^{-1})	(k_La_3=63.2 d^{-1}; k_La_4=62.6 d^{-1}; k_La_5=36.4 d^{-1})
Internal recycle	
Q_a = 0 ($m^3.d^{-1}$)	Q_a = 988.7 ($m^3.d^{-1}$)
Aeration energy	
EA = 1459.0 ($kWh.d^{-1}$)	EA = 1273.2 ($kWh.d^{-1}$)
	
Concentration of COD	



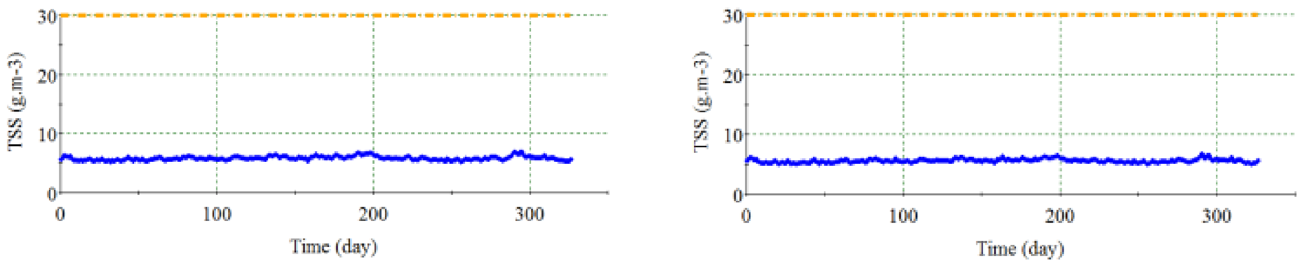
Concentration of BOD_5



Concentration of TN



Concentration of TSS



3 Discussion

After the optimization, all the effluent concentrations satisfy the out standard. Only TN closes the constraint that means the optimization is reasonable. The aeration energy reduces considerably compared to the actual operation of the WWTP, approximately by 30%. In addition, the aeration energies of two WWTPs are quite similar, but the Benchmark WWTP operates better than Verulam WWTP nearly by 15%.

The aeration policy for the aerobic tanks decreases from high to low. This is suitable for nitrification to avoid exceeding the TN output, especially for the Verulam WWTP. As to the Benchmark WWTP, although the aeration policy also decreases, but insignificantly, because this WWTP has the internal recycle flow back to the first tank.

The results show that the stable aeration policy (that does not change over time) will be quite energy-consuming when the influent concentration changes significantly, because the highest aeration policy must be set to treat the highest pollutant concentrations. When pollutant concentrations are low, the high aeration policy will be costly.

4 Conclusion

The results show that the Benchmark WWTP operates better than the Verulam one in terms of aeration energy. The Benchmark WWTP, which uses a pump to recycle the liquid to the first tank, extends the residence time in the tanks to treat pollutants. This reduces their concentrations, and hence, the aeration energy, almost by 15%. The Verulam WWTP is challenging to control the residence time in the tanks; therefore, we should find a right aeration policy to satisfy the discharge standards; otherwise, the concentration of TN exceeds effluent standard and costly aeration energy. Thus, the Benchmark wastewater treatment method is better than the Verulam one. Also, the Benchmark WWTP is easy to control the effluent by internal recycling. Although the results of the two methods of wastewater treatment show that energy saving of the aeration system is not much different, it provides researchers and designers with reliable information to be confident in deciding to choose the method to suit the reality.

The scope of this article is limited to methods of treating activated sludge wastewater by microorganisms that are available in the water. When adding other substances to support the wastewater treatment process, it is necessary to measure and check the parameters carefully.

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