Cost minimization in a full-scale conventional wastewater treatment plant: associated costs of biological energy consumption versus sludge production

S. Sid, A. Volant, G. Lesage and M. Heran

ABSTRACT

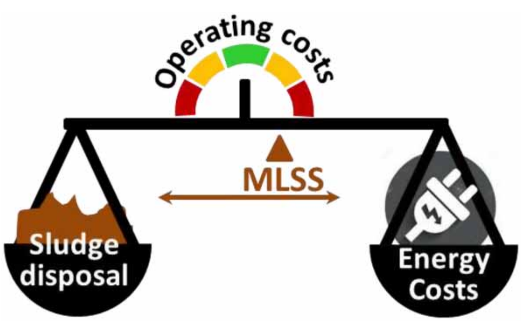
Energy consumption and sludge production minimization represent rising challenges for wastewater treatment plants (WWTPs). The goal of this study is to investigate how energy is consumed throughout the whole plant and how operating conditions affect this energy demand. A WWTP based on the activated sludge process was selected as a case study. Simulations were performed using a pre-compiled model implemented in GPS-X simulation software. Model validation was carried out by comparing experimental and modeling data of the dynamic behavior of the mixed liquor suspended solids (MLSS) concentration and nitrogen compounds concentration, energy consumption for aeration, mixing and sludge treatment and annual sludge production over a three year exercise. In this plant, the energy required for bioreactor aeration was calculated at approximately 44% of the total energy demand. A cost optimization strategy was applied by varying the MLSS concentrations (from 1 to 8 gTSS/L) while recording energy consumption, sludge production and effluent quality. An increase of MLSS led to an increase of the oxygen requirement for biomass aeration, but it also reduced total sludge production. Results permit identification of a key MLSS concentration allowing identification of the best compromise between levels of treatment required, biological energy demand and sludge production while minimizing the overall costs.

Key words | conventional activated sludge, cost optimization, energy consumption, modeling, sludge production, wastewater treatment

S. Sid
A. Volant
G. Lesage (corresponding author)
M. Heran
IEM (Institut Européen des Membranes), UMR 5635 (CNRS-ENSCM-UM), Université de Montpellier,
Place E. Bataillon,
Montpellier F- 34095,
France
E-mail: *geoffroy.lesage@umontpellier.fr*

HIGHLIGHTS

- Aeration is the highest energy demand operation within the activated sludge process.
- Increasing the MLSS concentration leads to a decrease in cost associated with sludge management.
- Increasing the MLSS concentration leads to an increase in cost associated with biological aeration.
- Optimal MLSS concentration could be determined with a modeling and simulation strategy.



doi: 10.2166/wst.2017.423

INTRODUCTION

Climate changes and resource scarcities are the main key challenges facing the world in the 21st century. According to the World Health Organization, 36% of the world's population, corresponding to 2.5 billion people, still did not have access to wastewater treatment (WWT) facilities in 2011. In developed countries, WWT accounts for about 3% of the electrical energy load (Curtis 2010). Optimization of WWT management is a major challenge in economic and social development and public health. And, even if the activated sludge process is the most widely used intensive WWT for domestic sewage in the world, it is still a high energy demand system. Indeed, a typical value for a domestic wastewater treatment plant (WWTP) energy consumption is about 0.6–1 kWh/m^3 of wastewater treated, and about half of this is for electrical energy to supply air for the aeration tanks (Curtis 2010; McCarty *et al.* 2011).

The energy demands in WWTPs, based on the conventional activated sludge (CAS) process, are for biological aeration, mechanical suspended solids mixing and recycling, and solid waste dewatering and pumping. Aeration usually accounts for about 30–60% of electricity consumption, followed by sludge treatment (25–65%) and pumping (15–20%) (Liu *et al.* 2011; Plappally & Lienhard 2013). Table 1 presents the synthesis of energy consumption in waste water treatment. This synthesis comes from Smith (1973, 1978) and Pabi *et al.* (2013).

Thus, aeration optimization is of great significance and would lead to big savings of both energy and money for WWTP operators. Operational costs associated with sludge management (disposal and treatment of excess sludge) are often considered as important economic problems when dealing with activated sludge (Liu & Tay 2001). Moving from the CAS process to an extended aeration process results in a decrease of about 30% in sludge production, which consequently leads to a decrease in sludge treatment and disposal costs. To minimize excessive sludge production, Mahmood & Elliott (2006) proposed two approaches, based on either post treatment of the excess sludge (which could be exposed to heat treatment, chemical oxidation or sludge digestion) or based on *in situ* process reduction of the sludge production. More attention is currently given to *in situ* sludge reduction rather than post treatment of sludge that requires extra cost (Guo *et al.* 2013). Indeed, several methods have been proposed to optimize the process parameters to lower sludge production such as uncoupling metabolism, maintenance metabolism, lysis-cryptic growth, and worm predation technology (Wei *et al.* 2003). On a laboratory scale, using a CAS reactor, Abbassi *et al.* (2000) showed that a reduction of about 25% of the sludge production could be achieved by increasing the dissolved oxygen (DO) concentration from 2 to 6 mg/l. Low & Chase (1999) also reported that the sludge production could be reduced by 44% by increasing the mixed liquor suspended solids (MLSS) from 1.7 to 10.3 g/L. However, a long solids retention time (SRT) and high DO concentration require excessive aeration and a subsequent energy consumption that could increase operating costs. Therefore, it is necessary to determine the optimum operating parameters and conditions in order to achieve a cost effective minimization for sludge production and sludge line energy demand.

Modeling and simulation can significantly contribute to the understanding and design of CAS WWTPs and are useful tools in the selection of operational strategies that improve process stability, effluent quality and operational costs. In a 'process-based' model, the WWTP is described by two interconnected sub-models: the activated sludge model, which describes the biological degradation of organic matter and nutrients, and the settler model, which describes the separation process between particulate and dissolved fractions of the activated sludge (Grau *et al.* 2007; Szilveszter *et al.* 2010). Since the early 1970s, there have been numerous studies on activated sludge system modeling in the literature (Siegrist & Tschui 1992; Çinar *et al.* 1998; Carucci *et al.* 1999; Makinia *et al.* 2002; Jeppsson *et al.* 2013). However, short-term data have been used in most modeling studies, and the influence of operating parameters on WWTP operating costs associated with biological treatment and sludge management have been rarely studied. Based on the carbon oxidation processes, nitrification and denitrification and biological phosphorus removal, activated sludge models (ASM1, ASM2/ASM2d and ASM3) have been proved to be excellent tools for biological reaction modeling (Nuhoglu *et al.* 2005). These models are currently applied in a lot of commercial software dedicated to the modeling and simulation of biologically-based WWTPs, such as GPS-X, SIMBA, AQUASIM, BioWin, EFOR, STOAT and WEST (Olsson & Newell 1999; Gernaey *et al.* 2004).

By collecting and analyzing three years of monitoring data from the CAS plant of a WWTP in the Montpellier area, this study aimed to (i) assess the energy consumption and operating costs of the plant, (ii) validate and apply a

Table 1 | Energy used for secondary wastewater and sludge treatment processes

	Energy intensity	kWh/m^3	kWh/p.e./year
Secondary treatment (CAS)	Aeration without nitrification	0.16–0.14	11–10
	Aeration with nitrification	0.26–0.25	18.9–18.25
	Return sludge pumping	0.012–0.0083	0.85–0.59
	Secondary clarifiers	0.011–0.0019	0.76–0.14
Sludge treatment	Sludge pumping	0.00044–0.00017	0.031–0.012
	Gravity thickener	0.0023–0.00036	0.16–0.026
	Dissolved air flotation	0.018–0.012	1.3–0.88
	Belt filter	0.0057	0.4
	Direct centrifugation	0.032–0.019	2.3–1.4

mathematical model to simulate the full scale plant in transitory phase, and (iii) propose energy saving strategies to reduce operating costs with regards to energy consumption and sludge production.

MATERIALS AND METHODS

WWTP description

A WWTP located in the area of Montpellier was selected as a reference case study. This plant began sewage treatment in 2008 and was designed to treat 4,680 m^3/day of sewage with a nominal capacity of 24,000 equivalent inhabitants (eq. inh.). The average flow was recorded between January 2013 and October 2015 at 112 m^3/h (with a maximum peak flow of 446 m^3/h). The characteristics of the wastewater at the inlet of the case-study WWTP are presented in Table 2.

The biological treatment (i.e. CAS treatment) consists of a contact tank (150 m^3) equipped with an agitator (1.5 kW), an anaerobic tank (1,200 m^3) equipped with two agitators (4 kW each). Three slow agitators (4 kW each) and membrane diffusers placed in the aerated tank (4,650 m^3) provide mixing and aeration of mixed liquor. Sludge effluent separation is achieved by a secondary clarifier (with a total surface area of 979 m^2) and the sludge is finally dewatered by centrifugation.

Table 2 | WWTP influent concentrations recorded during the studied period

Parameters	Units	Concentration
COD	mg/L	792 ± 209
MLSS	mg/L	427 ± 158
BOD	mg/L	309 ± 88
TKN	mgN/L	66 ± 16
N-NH_4	mgN/L	45.7 ± 8
Pt	mg/L	7 ± 2

Modeling methodology

Three years of operating data from 2013 to 2015 were gathered and used to develop a dynamic simulation model with the GPS-X (v.6.5) software package (Hydromantis Inc., Ontario, Canada).

The model layout of the WWTP used for simulation is given in Figure 1. The *Mantis* model, which is similar to the *Activated Sludge Model No. 1* (ASM1), was used for biological processes, and the *CODstates* influent model was used for influent characterization. The clarification process was modeled using a *Simple 1D* model (Takács *et al.* 1991).

Daily average values of influent flow rate, mixed liquor suspended solids in the aeration tank ($MLSS_r$) and influent concentrations (chemical oxygen demand (COD_{in}), ammonium (NH_{4in}), and total Kjeldahl nitrogen (TKN_{in})) were used as input for the model. Oxygen transfer efficiency of the fine bubble diffusers was controlled by setting the DO concentration at 2 mg/L and corrected values of the alpha factor (which allowed the oxygen transfer rate in an activated sludge reactor to be corrected), based on Equations (1) and (2) (Drews & Kraume 2005), were added as input

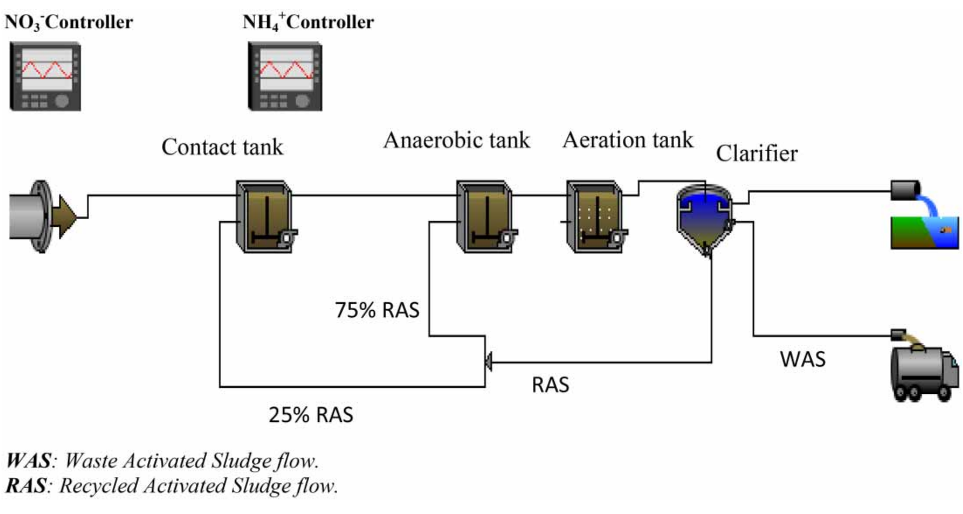


Figure 1 | WWTP layout in GPS-X software.

aeration parameters.

$$\phi_{O_2} = \alpha K_{la}(C* - C) \quad (1)$$

$$\alpha = e^{-0.088MLSS} \quad (2)$$

where:

ϕ_{O_2}: Oxygen transfer rate (mg/L/day)
α: Corrective factor for oxygen transfer rate (–)
K_{la}: Oxygen mass transfer coefficient at field conditions (1/day)
C*: DO saturation concentration at field conditions (mg/L)
C: DO concentration in the reactor (mg/L)
MLSS: Mixed liquor suspended solids concentration (g/L)

The nitrification-denitrification cycles in the aeration tank were optimized by the use of two ON/OFF controllers for NH_4^+ and NO_3^- effluent concentrations. Table 3 shows NH_4^+ and NO_3^- effluent concentration limits for aeration cycles.

In order to find the operating parameters for energy saving strategies, the virtual plant was then simulated during three years of operation by setting the MLSS concentration from 1 to 8 g/L and using the real influent flow and composition.

RESULTS AND DISCUSSION

Modeling validation

The WWTP model validation in the GPS-X software was done by comparing modeling simulations with the following experimental data: (i) MLSS concentration in aeration tank; (ii) effluent quality (NH_4^+ and NO_3^-); (iii) aeration, mixing and recirculation energy consumptions; (iv) annual sludge production.

MLSS concentration

MLSS concentration in the aeration tank was calibrated with a variation of the waste activated sludge (WAS) flow recorded between 7 and 25 m^3/h.

Table 3 | Aeration cycle for nitrogen compound removal in GPS-X modeling

ON/OFF controllers	Stopping aeration	Restarting aeration
NO_3^- (mgN/L)	3	0
NH_4^+ (mgN/L)	0.5	2.5

Modeling and experimental data of MLSS concentration are presented in Figure 2. MLSS concentrations varied from 2 g/L to 10 g/L with an average of 5 g/L. It appears that simulated MLSS concentrations are close to experimental data, and the mean relative error was calculated to be around 17%. This error is in the range of the instrument measuring accuracy and the uncertainty of measurement of the WWTP analytical laboratory.

As shown in Figure 2, and as agreed with the operator, it is possible to distinguish three distinct periods of MLSS concentrations in the aeration tank:

- A relatively stable period in 2013 with an average of 3.49 gMLSS/L.
- A period with higher values and greater variability in 2014 with an average of 5.19 gMLSS/L.
- A period with even higher values and significant variability in 2015 with an average of 7 gMLSS/L.

These different periods will be used to extend the whole simulation.

Effluent quality: NO_3^- and NH_4^+ effluent concentrations

With a DO controller fixed at 2 mg/L within the GPS-X software, the modeling data of NH_4^+ and NO_3^- concentrations were assessed and compared to the experimental data analysis from the WWTP analytical laboratory (with a frequency of one measurement per month) (Figure 3(a) and 3(b)).

Figure 3(a) and 3(b) indicate that modeling data of effluent concentrations of NH_4^+ and NO_3^- are consistent with experimental data. NH_4^+ effluent concentrations are mostly below the concentration limits of the WWTP designer (2.5 mgN/L) and always respect the rejected levels for TN (10 mgN/L). NO_3^- effluent concentrations are mostly below the limits of the WWTP designer (3 mgN/L). The peaks of NO_3^- concentrations measured were explained by an insufficient recirculation flow and a too-high oxygen concentration in the aeration basin.

Energy consumption for aeration, mixing and recirculation

Aeration: In order to ensure that energy consumption from GPS-X software was valid and uniform, GPS-X data were compared to the WWTP aeration consumption. The WWTP consumption was calculated by multiplying the compressor power by the operating time. As expected, mean RSD between those two values was around 8%, confirming the relevance of the modeling strategy.

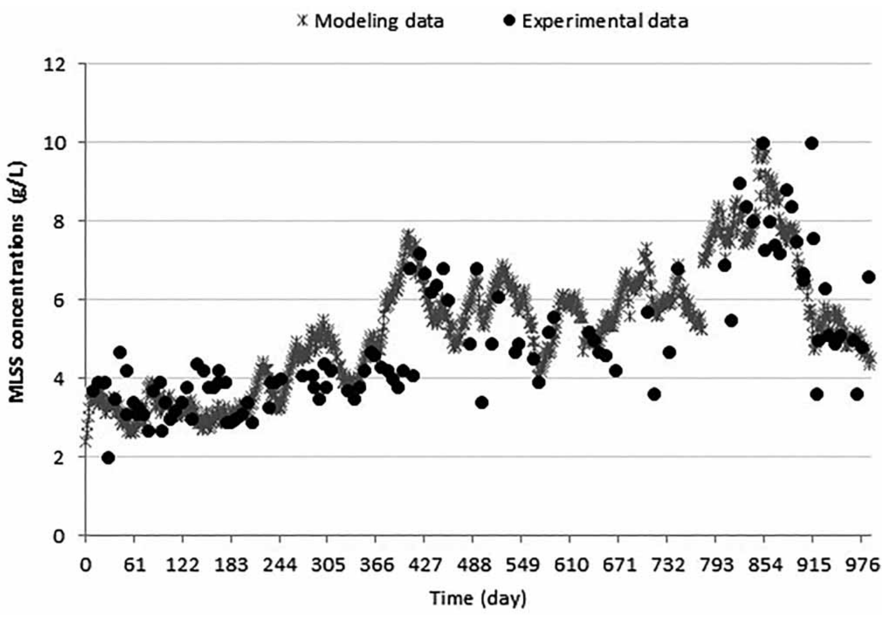


Figure 2 | Variations of MLSS in the aeration tank over time (modeling and experimental data).

Mixing energy in the GPS-X model was done on a 'per unit volume' basis by adjusting the power per unit volume. Daily energy consumption for mixing was calculated by multiplying stirrer power (contact tank, anaerobic and aeration tanks) by stirrer operating time. Then, the mixing power per unit of volume (kW/m^3 of tank volume) were entered into the GPS-X software. The values were around 10 W/m^3, 6.7 W/m^3 and 2.6 W/m^3 for the contact tank, the anaerobic tank and the aeration tank, respectively.

Recirculation and pumping energy (RAS) in the GPS-X are calculated by multiplying the hydraulic head and headloss by the pumping flow divided by the pump efficiency. The total hydraulic head was set to 7.8 m and a constant pump efficiency of 0.7 was applied. The mean RSD between those two values was around 10%, confirming the relevance of the parameters.

The average of modeled and calculated energy consumption for RAS and aeration are resumed in Table 4.

Sludge production

Table 5 presents the annual simulated and calculated sludge production.

Table 4 shows that the sludge production is well simulated by the GPS-X software. The comparison between calculated and modeled data enables the calculation of a mean RSD at around 2.13% for the three years' data, which confirms the relevance of models used during the GPS-X simulation.

Evaluation of specific energy consumption

The distribution of energy consumption per process is presented in Figure 4. For a total energy consumption of 0.82 kWh/m^3, the biological treatment was the main energy consumer process of the plant and accounted for 68% of the total energy consumption. Within this biological process, aeration for the oxygen supply was found to be the highest energy consuming process at about 64% of the total biological treatment energy consumption (Figure 5).

Impact of MLSS concentration on sludge production and energy consumption for biological treatment

In order to assess the impact of MLSS concentration on both sludge production and energy consumption, three specific periods were investigated (Table 6).

According to Table 5, the increase of MLSS concentration from 3 g/L to 7 g/L results in a decrease in sludge production. On the one hand, high MLSS concentration (high SRT) leads to minimization of the sludge production, which is mainly due to higher endogenous decay (transformation of volatile suspended solid (VSS) to gas). On the other hand, the biological energy consumption increases by approximately 37% due to higher sludge age. The impact of MLSS concentration on the energy consumption of these processes is presented in Figure 6.

The analysis of biological energy demand (Figure 6) shows that the increase in energy use was mainly due to

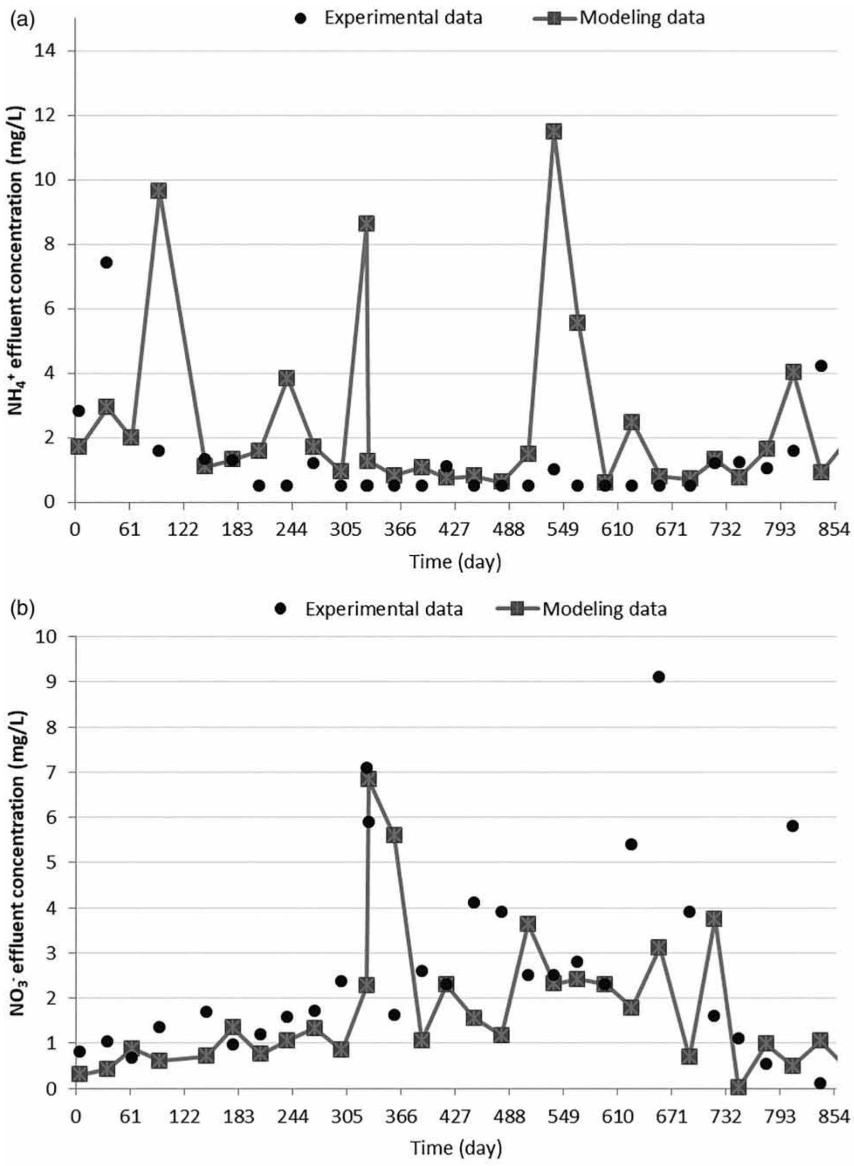


Figure 3 | Effluent concentration variations over time (a) NH_4^+ (b) NO_3^-.

Table 4 | Calculated and modeled energy consumption in the WWTP case study

	Calculated data (kWh/m^3)	Modeling data (kWh/m^3)	RSD (%)
Mixing	0.12	0.13	8
RAS	0.061	0.055	10
Aeration	0.36	0.35	3

Table 5 | Modeled and calculated data for sludge production

Year	2013	2014	2015
WWTP sludge production (kg/j)	615	563	540
Modeled sludge production (kg/j)	620	554	551
RSD (%)	0.8	1.6	4

aeration. In fact, an increase in MLSS from 3 g/L to 7 g/L resulted in an aeration increase of 57%, a mixing energy increase of 8% and a recirculation electricity demand of 3%. Increases in energy consumption arise from both worse oxygen transfer and an increase of endogenous process at high MLSS concentration.

Toward a minimization of overall costs

The WWTP was successfully modeled during 957 days of operation with special attention given to sludge production and energy consumption. Moreover, the reliability of the model was proved for a wide range of MLSS concentrations.

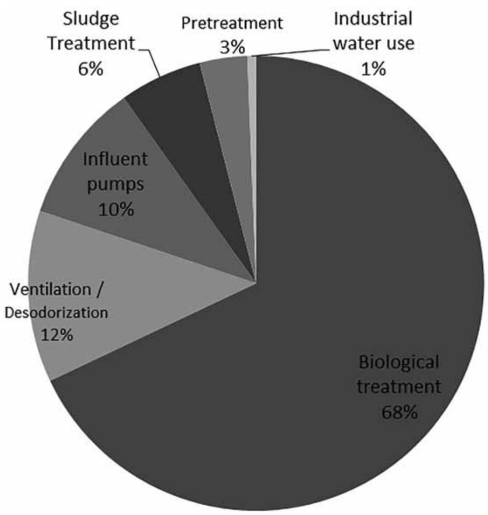


Figure 4 | Distribution of energy consumption per processes in the WWTP case study.

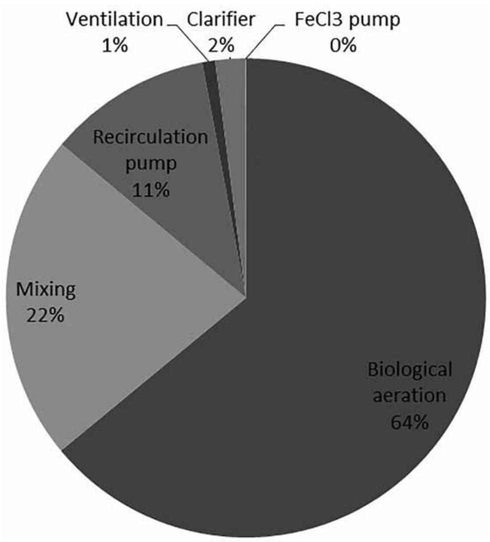


Figure 5 | Distribution of energy consumption within WWTP biological treatment.

Table 6 | Sludge production (10^3 kg of dry matter) and energy consumption (MWh) according to the concentration of MLSS

	From day 1 to 264 (264 days)	From day 357 to 624 (268 days)	From day 686 to 957 (272 days)
Average MLSS concentration (g/L)	3	5	7
WWTP sludge production (10^3 kg of dry matter)	161.3	153.8	150
Modeling sludge production (10^3 kg of dry matter)	169.1	159.3	147.5
WWTP energy demand[a] (MWh)	458	596	627

[a]Aeration + Mixing + RAS pumps energy consumption.

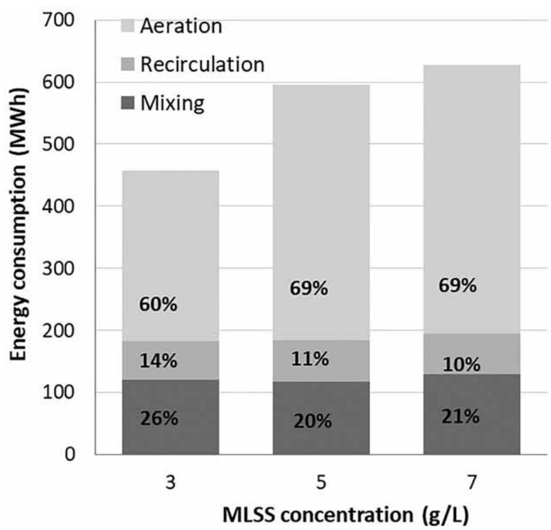


Figure 6 | Energy consumption due to biological treatment for different MLSS concentrations.

Thus, in order to minimize the overall WWTP costs, the simulation was reloaded with a fixed MLSS concentration. The virtual plant was indeed simulated during three years of operation by (i) setting the MLSS concentration from 1 to 8 g/L and (ii) using the real influent flow and composition. The aeration energy consumption and the sludge disposal cost are seen in Figure 7.

Energy demand versus sludge production

Specific energy consumption (kWh per treated cubic meter) and specific sludge production (kg dry solids per treated cubic meter) variation at different MLSS concentrations are presented in Figure 7.

One solution is for operators to be able to, on the one hand, compare specific power consumption (kWh/m^3) with specific sludge production (kg/m^{-3}) and, on the other hand, the concept of cost. The cost data of the studied WWTP are presented in Figure 7(b). The cost data used in the optimization analysis were calculated by fixing the price per kilowatt hour at 0.1€ and the sludge disposal cost at 45€ per ton of thickened fresh sludge (with a dry matter content of 20%, i.e. 0.225€ per kg of dry solids). WWTP data analysis shows a total energy consumption of 0.85 kWh/m^3 and a sludge production of 0.22 kg/m^3 of treated water, resulting in an overall cost of 0.1345 €/m^3. The overall cost trends (Figure 7(b)) show that an ideal MLSS concentration can be found to minimize this cost. The optimal concentration found is 3.625 g_{TSS}/L. This solution results in 'distributable earnings' per cubic meter of treated water of 0.1254 €/m^{-3} compared to 0.1345 €/m^{-3} under usual conditions.

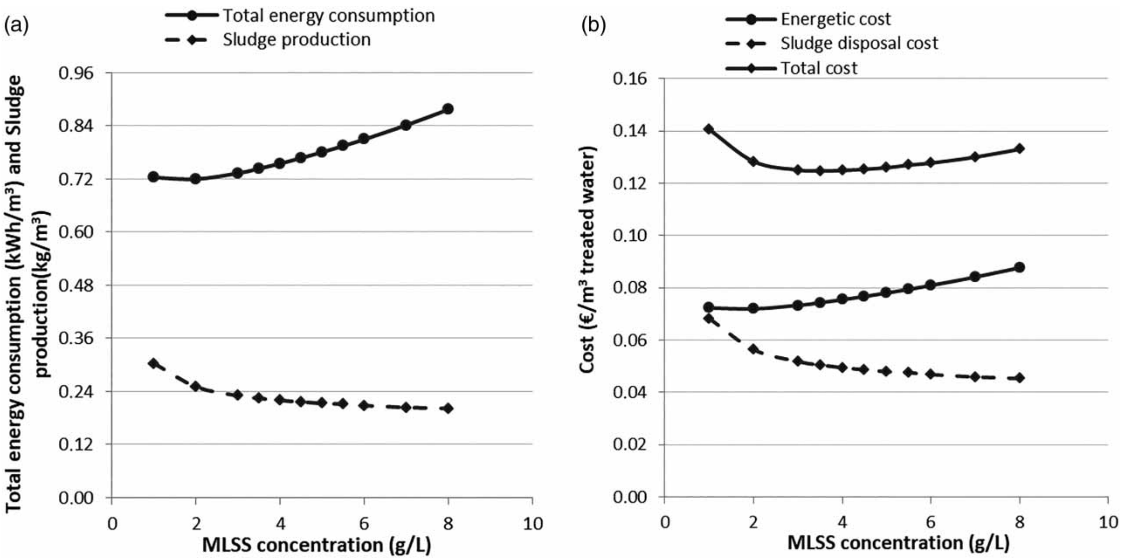


Figure 7 | (a) Energy consumption, sludge production and (b) overall costs versus MLSS concentration.

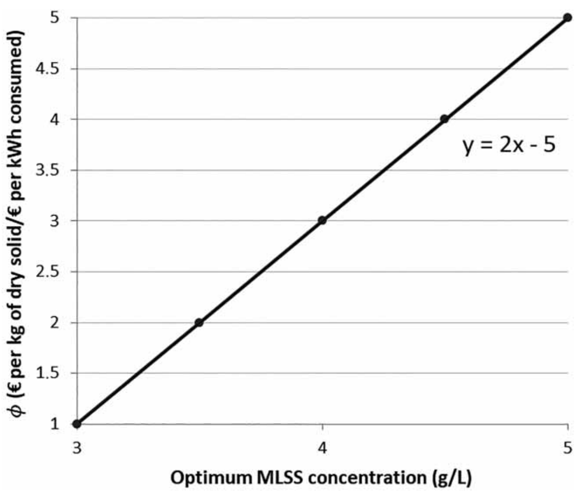


Figure 8 | Impact of ϕ ratio on optimum MLSS concentration.

Costs optimization

Costs could be linked to WWTP size, plant equipment, local regulations, transportation costs and sludge characteristics (Schaller *et al.* 2010). Nevertheless, the costs due to WWTP operations vary greatly depending on the local conditions due to differences in electricity costs and sludge management. Thus, total operation costs were calculated for different sludge disposal costs at a constant energy cost (0.1 €/kWh). The calculation was, more broadly, done by the introduction of a ratio (ϕ) to take into account sludge cost fluctuations. Figure 8 presents the total operating cost per m^3 of treated water versus MLSS concentrations at a constant energy cost: 0.1 €/kWh and at different sludge disposal cost according to the ϕ ratio (Equation (3)) value.

$$\phi = \frac{per\ kg\ of\ dry\ solids}{per\ kWh\ consumed} \quad (3)$$

Contrary to expectations, a linear correlation is observed between the relationships of the optimum MLSS concentration to the normalized ϕ coefficient. Figure 8 thereby enables the determination of the optimal MLSS concentration for a fixed charge of 0.1 €/kWh and variable sludge disposal costs.

CONCLUSION

Through the study of the energy consumption distribution in a full scale activated sludge process WWTP, it can be seen that the secondary treatment is the major energy-using part (68%). This high energy consumption is mainly due to the aeration supply (44% of the total plant energy consumption) which is essential for achieving the level of required treatment. Then, the MLSS concentration was identified as a crucial parameter impacting both energy consumption and sludge disposal cost. The CAS was also conducted at three MLSS concentration to calibrate the model. A reduction in the MLSS concentrations results in energy saving for aeration. But on the other hand the reduction in MLSS concentration increases the sludge production, which is the second most important cost item. To tackle these opposing effects, a ϕ ratio, comparing the sludge disposal (€/kg of dry solids) to the energy costs (€/kWh), was defined. Once the cost of electricity has been fixed, simulation results show that the optimum MLSS concentration, which results in lower overall costs, increases linearly with the sludge disposal cost. According to this trend, the WWTP operators should find the optimum MLSS concentration which delivers the lowest cost per cubic meter of treated water. By working at 3.625 g_{TSS}/L, the total treatment cost is around 0.1254 €/m^{-3} which allows for savings of more than 10%.

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First received 16 March 2017; accepted in revised form 3 July 2017. Available online 17 July 2017