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OBTAINING A GUIDE OPERATOR OF WASTEWATER TREATMENT BY SBR PROCESS USING SIMULATION AND SENSITIVITY ANALYSIS

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Abstract

The main aim of this paper was to obtain, on the base of sensitivity analysis, a guide for correct operation of the sewage treatment plant at Eforie Sud which uses sequential batch reactors (SBRs). For this purpose several original procedures were realized. An initial regression model was obtained using the SBR simulation with STOAT 5.0 software, confronted with the process data collected on-line. As it was expected, the range of these data was small, corresponding to the usual domain of SBR exploitation. Another original idea was to extend this database by random generation of 100 sets of process data, and the values of effluent pollutants concentrations for each set were calculated using the simulator STOAT 5.0. Using an original two/step regression based on these data, good equations for the effluent pollutants concentrations were obtained. The last original idea was to use these equations in the framework of a sensitivity analysis by Monte Carlo simulation and to establish several quantitative results important for correct process operating: when the effluent polluant concentration increases over the accepted value, the corresponding value of input concentration must be decreased by dilution with fresh water, and/or by increasing the reaction time. The simulation of these actions can be made with the corresponding regression equations.

Keywords: SBR process, simulation, sensitivity analysis

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1. Introduction

Wastewater treatment is the set of measures and processes by which the chemical or bacteriological impurities contained in the wastewater are reduced below certain limits so that these waters do not harm the receptor in which they are evacuated and do not endanger their subsequent use. Wastewater treatment plants are currently a whole (Dhote et al., 2012). It is no longer possible to develop and delimitate the processes, because physical, chemical and biological processes succeed and overlap in the same objects (Tchobanoglous et al., 2003).

The technologies used for household water treatment have seen significant developments over the last 20-25 years due to the requirements imposed not only by environmental legislation, but also by the European Parliament's directives on the promotion of the use of energy from renewable sources.

The dynamics of technological changes result from the emergence of new treatment solutions, overlapping on the continuous modification and refinement of the equipment and installations (Gupta and Ali, 2013), as well as from the generalization of the automations in the management of the technological processes. Wastewater treatment technologies involve the alternation of aerobic and anaerobic (cyclic) processes for the partial or total elimination of undesired substances. This is done by creating separate reactors such as dephosphating, denitrification, and nitrification, followed by different recirculation possibilities depending on the technology. In the technological schemes within a treatment plant, depending on the operating regime,

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different types of reactors are used that can be grouped as follows:

- continuous-flow reactors (with piston flow, total mixture etc.);
- sequencing batch reactors (SBR).

Processes in SBR are identical to those in continuous-flow reactors, with the exception that aeration and settling occur in the same basin (Cabrera et al., 2011). Here the processes take place sequentially, compared to the classic version, where the two phases take place simultaneously (Tobolcea et al., 2010).

In the last years wastewater treatment modelling has begun to use several computer simulators (Al-Shahwan et al., 2016), such as SPHASE (Meister and Rauch, 2016), ASIM, BioWin (Liwarska-Bizukojc and Biernacki, 2010), STOAT (Mohamadi et. al., 2015).

2. Wastewater treatment using the SBR

Although there are several configurations of SBRs, the basic process is similar. The installation consists of at least two tanks equally equipped with a common orifice that can be switched between them. The tanks have a "flow through" system in which the raw wastewater (influent) is introduced at the entrance and the treated water (effluent) flows through the exit. While one tank is in the settling/decantation mode, the other one is in the aeration or filling phase.

SBR is a variant of ASP (activated sludge process). All the biological water treatment phases take place in a single tank. This differs from the conventional activated sludge process flow, which requires separate reservoirs for aeration and sedimentation of the treated water.

These water treatment plants are made up of several tanks, which are equipped with electromechanical equipment such as pumps, mechanical and gravity filters, air diffusers, aerators, mixers and overhead rooms equipped with blowers, drying and packing sludge equipment, chemical dephosphating, disinfection and control sets etc.

2.1. SBR process description

SBR cleaners use saturated and dry activated sludge in the treatment process. The SBR system consists of a single basin in which cyclic sewage processes take place. It is an active sludge basin in which equalizing, aeration and decanting take place. SBR allows the elimination of nitrogen and phosphorus by anaerobic mixing, and by switching on/off the electro-blowers during the reaction processes. These are operated through the automated control system.

Basically, the SBR system is a set of filling and evacuation tanks. Each tank in the SBR system is filled over a period of time and then functions as a discontinuous reactor. After the desired treatment, the mixed liquid is allowed to settle and the clarified supernatant is then discharged from the reservoir. The cycle for each tank in a typical SBR is divided into five distinct periods: filling, reaction, sedimentation, settling (evacuation) and idle as shown in Fig. 1. There are several types of filling and reaction periods, which vary according to aeration and mixing procedures. Extraction of excess sludge can take place near the end of the reaction phase or during sedimentation, evacuation or idle phases. The main feature of SBRs is the use of a single tank for multiple sewage treatment processes.

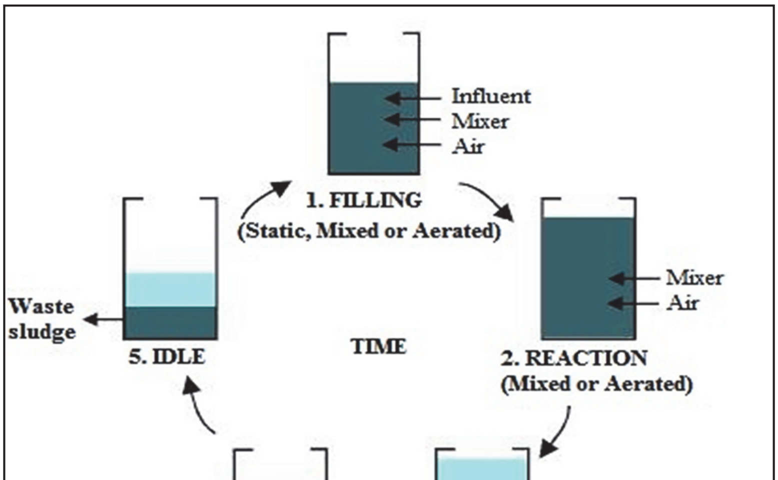

Fig. 1. SBR operation for each tank in a single cycle with the five distinct periods of Filling, Reaction, Sedimentation, Evacuation and Idle

Filling: The influent in the tank may be raw wastewater (filtered and without gravel) or primary effluent. The influent can be pumped or gravitationally introduced. The feed volume is determined on the basis of a number of factors, including the desired loading and retention time and the expected sedimentation characteristics of the organisms. The filling time depends on the volume of each tank, on the number of parallel tanks in operation and on the dimensions of the daily variations in the wastewater flow rate. In practice, any aeration system (for example by diffusion, float mechanics or jet) can be used. However, the ideal aeration system must be able to provide both a range of mixing intensities (from zero to full agitation), and flexibility of mixing without aeration. Level sensing devices, timers, or probes in the tank (for measuring dissolved oxygen or ammoniacal nitrogen) can be used to start and stop the aerators and/or mixers (Liu et al., 2017; Zhang and Chen, 2009).

Reaction: Biological reactions initiated during filling are completed during the reaction stage. As with filling, alternative conditions of low dissolved oxygen concentrations (e.g. mixed reaction) and high dissolved oxygen concentrations (e.g. aerated reaction) may be required. By extracting during the reaction, sludge is removed from the tank, this process being a means of maintaining or decreasing the volume of sludge in the tank and of reducing the volume of solids. The reaction time may be up to 50% or more of the total cycle time. The end of the reaction may be indicated by a time specification (for example, the reaction time will always be 1.5 hours) or a level controller in an adjacent tank (Alzate et. al., 2016).

Sedimentation: In a resting SBR (without inputs or outputs), the separation of the solids takes place in a tank that can have a volume of more than ten times bigger than the volume of secondary clarifier used for a conventional sludge plant activated in continuous flow. This major advantage in the clarification process results from the fact that the entire aeration tank serves as a clarifying agent in the period when there is no flow in the tank. Because all the biomass remains in the tank until a certain part has to be scattered, it is not necessary to provide the devices that ensure the continuous flow commonly found in conventional clarifiers. By means of contrast, the mixed liquid is permanently removed from the continuous flow aeration tank and passed through clarifiers only to have a major part of the sludge returned to the aeration tank.

Evacuation (Settling): The evacuation mechanism may consist either of a pipe fixed at a predetermined level with the flow regulated by an automatic valve, by a pump, or by an adjustable or floating spill located at or just beneath the surface of the liquid. In any case, the evacuation mechanism must be designed and operated in such a way as to prevent the discharge of floating materials. The time for evacuation may vary from 5 to over 30% of the total cycle time. However, the time during the evacuation phase should not be extended too much due to possible problems with the growing sludge (Trelles et. al., 2017).

Idle: The period between Evacuation and Filling is called Idle (Waiting). In spite of its name, this "waiting" time can be used effectively to extract the decanted sludge. While sludge extraction can occur quite rarely, for example once every 2-3 months, it is recommended to use sludge extraction programs to maintain process efficiency and sedimentation of the sludge (Poltak, 2005).

2.2. SBR modeling and simulation

Despite the fact that SBR is a new type of equipment, in the last decade were elaborated a lot of works dealing with SBR modeling and simulation.

Thus, a set of analytical equations that represent the effect ofthe operational parameters on the performance of a SBR was developed by Lobo et al. (2016). The obtained equations adequately represent the change of the organic substrate, ammonia, biomass, oxygenand soluble microbial products as a function of time within a single operation cycle of the SBR. The equations also predict the steady-state concentrations as a function of several operational parameters, avoiding the problem of performing a great number of simulations. Based on real SBR data, the biomass growth yield and the decay factor for two syntheticwastewaters were obtained. Using these coefficients, the proposed equations adequately predicted the biomass concentration in real cases.

Bournazou et al. (2013) proposed a fast and accurate optimization framework to compute optimal aeration policies in SBR processes under partial nitrification. The optimization framework aims to determine an optimal intermittent aeration profile which minimizes both the operation time of the SBR cycle and the energy required for aeration. Special consideration is given to the fact that the results not only need to be accurate but also to converge within a short time. Moreover, methods to avoid nitrate formation are analyzed and implemented. It is demonstrated that the implementation of a nonlinear model and the reduction of the optimization problem to three control variables are the keystones to an efficient solution strategy which achieves fast, robust, and accurate computation of the optimal intermittent aeration profile for any given conditions of the process. The optimization approach is so efficient that it can also be implemented with more complex models extended for a two-step nitrification-denitrification process (Ji and Chen, 2010).

The modeling using artificial neural networks (ANNs), nowadays a well established method to elaborate empirical models was applied in the field of SBR. Thus, De Lille et al. (2015) were used ANNs to estimate from pH-measurements the ammonium in an anaerobic ammonium oxidation SBR. A differential equations model was used to simulate the processes inside the reactor. The model employs Monod kinetics to describe the growth rates of the microorganisms and the death-regeneration concept to describe decay. The simulated ammonium concentration (broadened data set) was then used as target data for the training of different structures of two types of ANNs: multilayer feedforward neural network and adaptive-network-based fuzzy inference system. The ANNs were validated using new data from largely fluctuating influent conditions. Both types of ANNs were able to predict with good accuracy theammonium removal inside the SBR even while dealing withth elargely fluctuating influent conditions without the need of further training. This shows the potential that ANNs have to model the anaerobic ammonium oxidation process if enough and representative data is available for training.

Another ANNs application for SBR was proposed by Zaghloulet et al. (2018) to simulate aerobic granulation. Aerobic granulation is a complex process that, while proven to be more effective than conventional treatment methods, has been a challenge to control and maintain stable operation. There were used two ANNs. The first sub-model receives influent characteristics and granular sludge properties. These predicted parameters then become the input for the second sub-model, predicting the effluent characteristics. The model was developed with a dataset of 2600 observations and evaluated with an unseen dataset of 286 observations. The prediction R2 and RMSE were > 99% and < 5% respectively for all predicted parameters. The results of this paper show the effectiveness of data-driven models for simulating the complex aerobic granulation process, providing a great tool to help in predicting the behaviour, and anticipating failures in aerobic granular reactors.

A novel model-based adaptive control strategy for step-feed SBR was developed and compared with traditional fixed-parameters control strategy and statically optimal parameters control strategy under influent fluctuation period (Luo et al., 2014). The SBR was operated with automatic alteration of the operating parameters based on the numerical calculation results of fully coupled activated sludge model. Since the influent fluctuated from one cycle to another, model-based adaptive control strategy was applied to optimize the operating parameters of the SBR accordingly. By using the model-based adaptive control strategy, the average removal efficiencies for total nitrogen and total phosphorus achieved in fluctuation tests were over 84% and 98%, respectively. Compared to traditional fixed parameters strategy, the total nitrogrn removal efficiency was improved by 25.11%.

The purpose of the study of Kim et al. (2008) was to simulate and optimize the nitrogen removal of a SBR through the use of a simplified model derived from activated sludge model and iterative dynamic programming, while meeting the treatment requirements. Activated sludge simplified model contain five reactions with six component. Mass balances for all components related to carbon and nitrogen removal are formulated as nonlinear ordinary differential equations. A new performance index for SBR optimization is proposed on the basis of minimum area criteria that consider the minimum batch time and the maximum nitrogen removal so as to minimize the energy consumption. Choosing area as the performance index simplifies the optimization problem and the use of appropriate weights in the performance index makes it possible to minimize the time and energy of the SBR simultaneously. In the optimized system, the optimal set-point of dissolved oxygen affects both the batch time and energy savings. Simulation results by IDP-based SBR optimizations suggest that batch scheduling, the set-point trajectory of dissolved oxygen concentration and the amount of external carbon all require supervisory control in order to achieve the optimal energy-saving concentration of total nitrogen in the effluent. Simulation results of the SBR show that the total energy cost can be reduced by up to 20% for the aerobic phase and 10% for the anoxic phase with maximum nitrogen removal.

Soliman and Eldyasti (2017) have used operational data of a partial nitrification SBR at high nitrogen loading rates. A long-term dynamic and pseudo-state model was developed by BioWin software, which is similar with STOAT 5.0 simulator used in the present work. The calibrated model was able to predict accurately the daily effluent data and to simulate the rapid shift to partial nitrification.

Here we have presented only a small part from the recent multitude of papers dealing with SBR modeling and simulation.

3. Eforie Sud wastewater treatment plant

3.1. The WWTP

Eforie Sud Wastewater Treatment Plant (WWTP) belongs to S.C. RAJA S.A. and is located in the city of Eforie Sud. It takes over the wastewater from the Agigea, Tuzla, Techirghiol, Schitu, Costinesti, Eforie Nord and Eforie Sud cities through 14 pumping stations. The sewerage system serving the wastewater treatment plant is a unitary system. The Eforie Sud WWTP is designed for a load of 140,000 EI (equivalent inhabitants) in the season (summer period), and 69,000 EI off-season (winter time). The plant is sized at the capacities of 745 L/s (season) and 322 L/s (off-season).

The WWTP treats wastewater by SBR technology. The water enters the treatment plant through a duct, and then it is distributed to two channels that enter the grids room. An overflow for emergency situations, closed with a tap, is available in the entrance hall. There are two technological lines - a rare grid and a dense grid on each line. There is also a sand washer on each line. The sand washers remove the organic components from the sand contained in the sand separator, so that the concentration of organic substances is less than 5%.

The sand trap is equipped with a large bubble aeration device so that a separation of more than 97%

of the granular sand ≥0.2 mm occurs. Each sand trap is also provided with a fat compartment separated by a concrete wall from the sand separator. Through the openings in the dividing wall the fat that floats due to air intake reaches this compartment.

The raw water pumping station is a concrete home in which 4 submersible pumps are installed. Depending on the quantity of water, the transport is performed by 1, 2 or 3 pumps, one of the pumps being in reserve. The number of active pumps is controlled by a fill sensor. The pumps carry the water from the sand trap to the biowaste treatment chamber.

Phosphorus that cannot be eliminated in SBR by biological treatment is chemically precipitated by dosing a coagulant solution, namely ferric chloride.

The metered amount is adjusted to reach a total of 1 mg/L phosphorus in the evacuated effluent. The dosing of the coagulant is done directly at the pumping station before the biological treatment step. There are two coagulation tanks (each with a capacity of 15 m³) and a metering pump.

The pumps transport wastewater to a concrete distribution room, where two weirs with electrically operated armatures are installed, each assigned to a SBR reactor. They are normally closed. In order to fill a reactor, the proper weir opens.

The SBRs

Two SBRs with L l water depths = 50,3m 32,2m · 6,4m are provided. Each SBR tank is equipped with the following:

– aeration device which ensures oxygenation and operates the aerated diffuser plate on the whole surface of the basin floor;
– 2 aerators for each SBR;
– 2 Mega prop-type Wilo agitators;
– 2 HST-WKS-type settling devices;
– 1 excess sludge pump.

The disinfection station is located near the SBRs. The disinfection solution is chlorine dioxide. Chlorine dioxide will be produced, immediately before dosing, from hydrochloric acid and sodium chlorite. HCl (about 25-36%) and $NaClO_2$ (about 27.5%) are stored separately in two 10 m³ tanks. Both tanks are heated and thermally insulated. An emergency shower, an eyewash shower, and a gas detector are disposed at the disinfection station.

The pumping station, located east of SBR, is equipped with 4 dry pumps mounted in the basement, of which 3 pumps will work alternately and a pump will be in reserve. Wastewater is pumped through a 700 mm duct to the 2 existing exhaust pipes to the Black Sea.

4. Case Study - Simulation of SBR procedures using the STOAT 5.0 simulator

An important purpose of this paper is to simulate the SBR processes for sewage treatment at the Eforie Sud WWTP using the STOAT 5.0 simulator. Fig. 2 presents wastewater treatment plant flowsheet represented by STOAT 5.0 simulator, which comprises: the inlet channel, a coarse bar screen, a fine bar screen, a sand trap, and the chemical precipitation unit of the phosphorus, a balancing tank, the two parallel-bonded SBRs, wastewater outlet pipe and excess sludge outlet pipe.

The Balancing Tank is an alternative approach by connecting the SBR effluent line to an equilibrium tank that has been configured with an infinite volume and a zero discharge rate. At the end of each cycle, the balancing tank will contain all the effluent discharged during the simulation, and the evacuation results will provide the average parameters of the wastewater. SBR profiles can be further monitored by analyzing the evacuation results for the line leading to the balancing tank. Each pictogram in the scheme corresponds to an equipment in the treatment plant.

Input parameter values are those obtained from analyzes performed in the treatment plant's laboratory. Laboratory determination of nitrates, ammonium and phosphorus is performed on the basis of SR ISO 7890-1, SR ISO 7150-1 and SR EN 1189 and in accordance with their quality requirements. Determination of nitrogen, ammonium and phosphorus is performed with a DR 3900 HACH LANGE spectrophotometer.

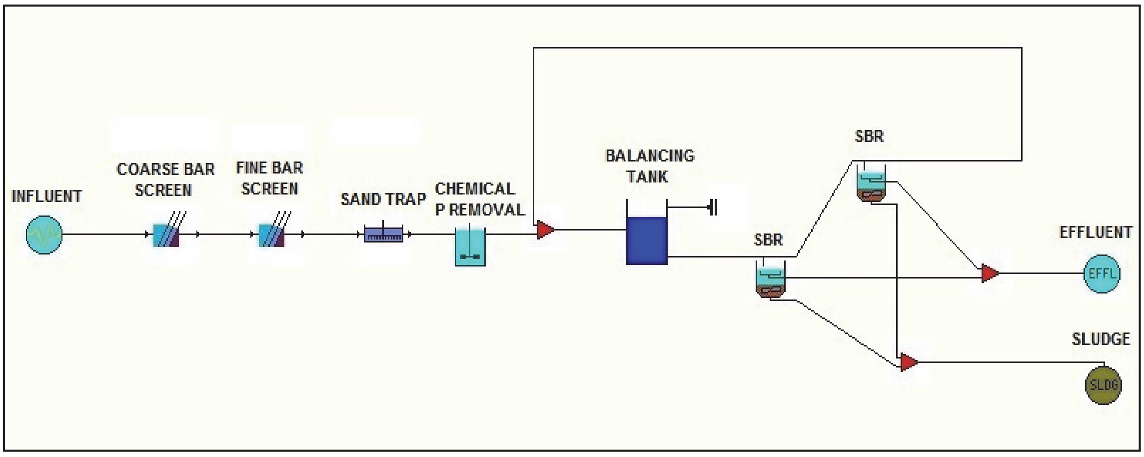

Fig. 2. Wastewater treatment plant flowsheet represented by STOAT 5.0 simulator

The filling time of the SBRs varies according to the inlet flow rate in the treatment plant. The influent is monitored by collecting samples (250 mL) from 30 to 30 minutes throughout this phase. The samples are mixed, homogenized, and an amount of 150 mL are taken for analysis. After the filling phase, the reaction and sedimentation phase follow. The middle and the end of settling phase, 250 mL of effluent samples are collected, of which 150 mL are homogenized, stirred and analyzed. The monitoring of the treatment plant is carried out through the SCADA system and thus the precise sampling time is known. Parameter values obtained in laboratory are introduced into simulator to obtain simulated concentrations. Tables 1 and 2 present the comparative results between the measured and the simulated effluent and the operating parameter for the input flowrate 500 m^3/h and, respectively 385 m^3/h. Similar results were obtained for the input flowrates of 250 m^3/h, 350 m^3/h, 375 m^3/h, 450 m^3/h, 658 m^3/h, and 1243 m^3/h (these input flowrates were randomly selected every two months for a one-year period).

The corresponding fits between simulated and experimental (measured) values of ammonia, nitrate and phosphorus effluent concentrations are presented in Figs. 3 – 5.

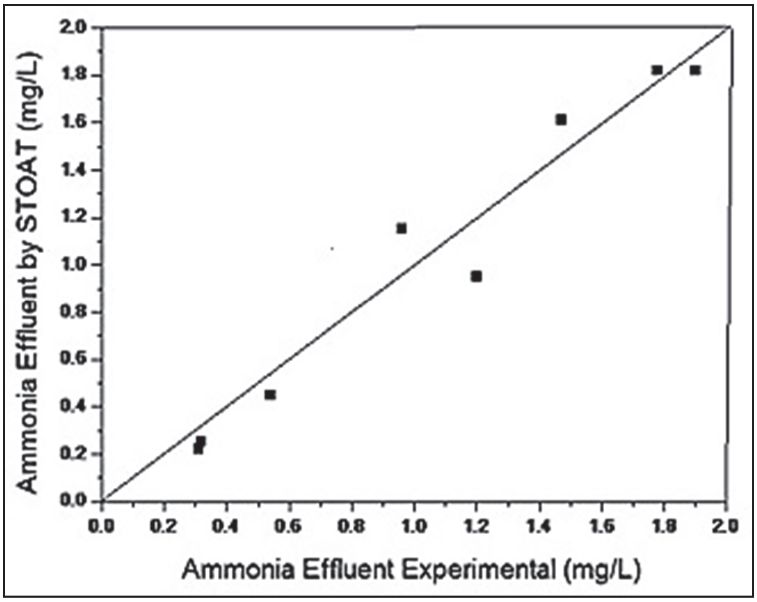

Fig. 3. Comparison of simulated and experimental values of ammonia effluent concentrations

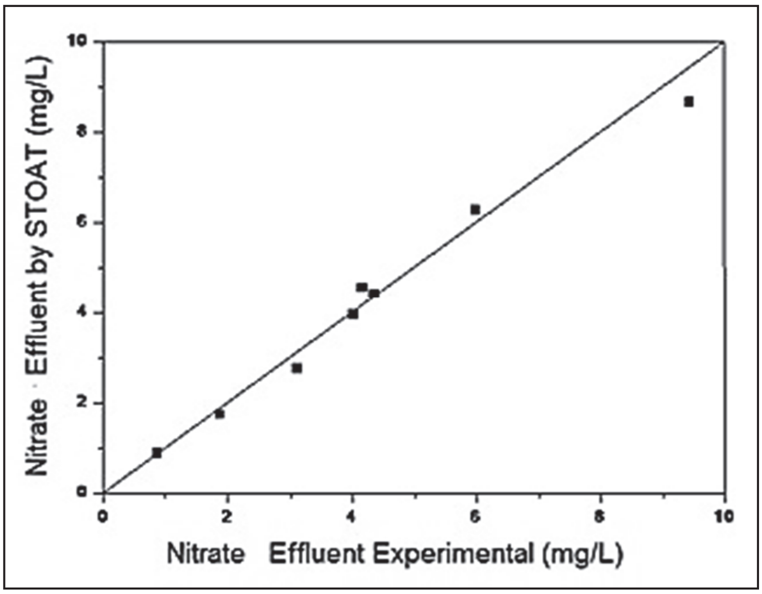

Fig. 4. Comparison of simulated and experimental values of nitrate effluent concentrations

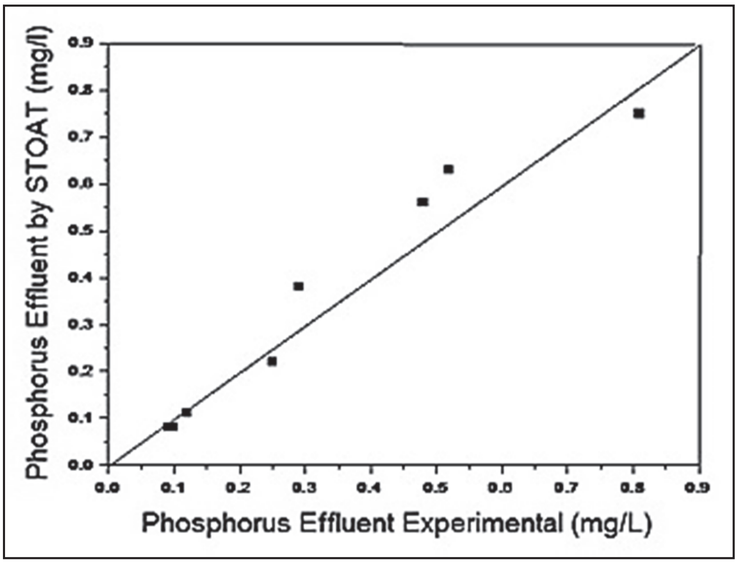

Fig. 5. Comparison of simulated and experimental values of phosphorus effluent concentrations

Table 1. Comparison of measured and simulated effluent characteristics (flowrate 500 m^3/h)

Influent	*SBR working time*	*STOAT effluent*	*Measured effluent*
Flow - 500 m^3/h	Aeration - 0.83 h		
Ammonia - 23.5 mg/L	Post Aeration - 1.17 h	Ammonia - 0.45 mg/L	Ammonia - 0,54 mg/L
Nitrate - 27.5mg/L	Reaction - 3.25 h	Nitrate - 8.66 mg/L	Nitrate - 9.42 mg/L
Phosphorus - 4 mg/L	Sedimentation - 0.67 h	P - 0.75 mg/L	P - 0.81 mg/L
	Settling - 0.78 h	N total - 9.11 mg/L	N total - 9.96 mg/L
	SBR_2 idle 2.00 h		

Table 2. Comparison of measured and simulated effluent characteristics (flowrate 385 m^3/h)

Influent	*SBR working time*	*STOAT effluent*	*Measured effluent*
Flow - 385 m^3/h	Aeration - 0.67h		
Ammonia - 30,31 mg/L	Post Aeration - 1.75h	Ammonia - 0.25 mg/L	Ammonia - 0,32 mg/L
Nitrate - 22,23 mg/L	Reaction - 4.37h	Nitrate - 4.54 mg/L	Nitrate - 4,16 mg/L
Phosphorus - 1,22 mg/L	Sedimentation - 0.33h	P - 0.38 mg/L	P - 0,290 mg/L
	Settling - 0.83h	N total - 4.78 mg/L	N total - 4,48 mg/L
	SBR_2 idle 2.42h		

5. Mathematical model of SBR

From Figs. 3-5 the good agreement between the measured and simulated values of variables can be observed. But, the measured values of variables correspond to the usual domain of SBR exploitation, respectively small values of the effluent pollutants concentration. The regression model obtained only for this data will be very local. In order to obtain a more general regression model the most important 6 independent variables with values on a more extended range were selected. These variables and the corresponding domains are:

x_1: input flowrate (m^3); $100.99 \leq x_1 \leq 1991.24$
x_2: input ammonia concentration (mg/L); $10.47 \leq x_2 \leq 79.29$
x_3: input nitrate concentration (mg/L); $3.32 \leq x_3 \leq 79.93$
x_4: input phosphorus concentration (mg/L); $1.16 \leq x_4 \leq 8$
x_5: aeration time (h); $0.25 \leq x_5 \leq 1.78$
x_6: reaction time (h); $1.21 \leq x_6 \leq 9.9$

Post-aeration time was considered constant, respectively 1.26 h.

The dependent variables are required parameters for the quality of the purified water and they must fall within the limits imposed by authorities, as follows:

y_{NH4} - the ammonium concentration in the effluent must not exceed the legal limit of 2 mg/L NH_4;
y_{NO3} - the nitrate concentration in the effluent must not exceed the legal limit of 25 mg/L NO_3;
y_{Ph} – the phosphorus concentration in the effluent must not exceed the legal limit of 1 mg/L Ph.

The six independent variables (x1-x6) are important parameters for the following reasons:

x_1 - input flowrate influences the residence time of water in SBR and, implicitly, the reaction time;
x_2 - input ammonia concentration influences the number of nitrifications to be carried out over a SBR cycle in order to obtain an ammonia-containing effluent which falls within the required limit imposed by the authorities;
x_3 - input nitrate concentration influences the number of denitrifications to be carried out over a SBR cycle in order to obtain a nitrate-containing effluent which

falls within the required limit imposed by the authorities;

x_4 - input phosphorus concentration influences the amount of coagulant required to obtain a phosphorus-containing effluent which falls within the required limit imposed by the authorities;

x_5 - aeration time influences the nitrification reaction and, implicitly, the removal of ammonium from the process;

x_6 - reaction time - is an important parameter because the ammonium, nitrate and phosphorus concentrations in the effluent depends on it; the longer the reaction time, the lower the effluent concentrations of these three parameters.

For the variables $x_1 - x_6$, 100 sets of values were randomly generated, and for each set the values of effluent of ammonia y_{NH4}, nitrate y_{NO3}, and phosphorus y_{Ph} concentrations were calculated using the simulator STOAT 5.0. Using the software DataFit 8.1 with the values of independent variables $x_1 - x_6$ and dependent variables y_{NH4}, y_{NO3}, and y_{Ph} the next regression equations from this 100 sets were obtained:

$$y_{NH_4} = \exp(1.98E-05*x_1 + 6.56E-02*x_2 + 3.63E-03*x_3 + \\ +2.15E-02*x_4 - 0.3266*x_5 - 0.4561*x_6 + 2.3016) \quad (1)$$

$$y_{NO_3} = -4.10E-05*x_1 + 2.87E-03*x_2 + 6.99E-02*x_3 + \\ +4.26E-02*x_4 - 0.3447E*x_5 - 0.4338 + 2.7520 \quad (2)$$

$$y_{Ph} = \exp(-4.16E-06*x_1 + 9.17E-04*x_2 + 2.16E-04*x_3 + \\ +6.34E-02*x_4 - 2.91E-02*x_5 - 4.77E-02*x_6 + 0.250819433 \quad (3)$$

Eqs. (1) and (2) are applicable for $y_{NH4} \leq 7$ and $y_{NO3} \leq 7$, and Eq. (3) for $y_{Ph} \leq 6.5$. The average percentage relative errors of equations (1) - (3) are high: 44.09% for Eq. (1), 38.15% for Eq. (2), and 37.38% for Eq. (3).

In order to refine this model, the sets of data corresponding to percentage relative errors less than 10% were selected. There were 30 sets for the values of effluent ammonia concentration, 28 sets for the values of effluent nitrate concentration, and 24 sets for the values of effluent phosphorus concentration.

Using again the software DataFit 8.1, the regression equations (4-6) for these data were obtained:

$$y_{NH_4} = -2.46E-06*x_1 + 6.44E-02*x_2 + 7.05E-03*x_3 + 2.59E- \\ -02*x_4 - 0.4665*x_5 - 0.4284*x_6 + 2.2066 \quad (4)$$

$$y_{NO_3} = 4.58E-05*x_1 + 3.44E-03*x_2 + 6.69E-02*x_3 - \\ -4.95E-02*x_4 0.3323*x_5 - 0.4077*x_6 + 2.6645 \quad (5)$$

$$y_{Ph} = -2.87E-05*x_1 - 6.02E-05*x_2 - 7.98E-05*x_3 + \\ +6.31E-02*x_4 - 1.65E-02*x_5 - 4.56E-02*x_6 + 0.3186 \quad (6)$$

The average percentage relative errors of these equations are very good: 3.69% for Eq. (4), 5.44% for Eq. (5), and 3.66% for Eq. (6). This very good agreement between simulated and regression values can be also observed in Figs. 6-8. The coefficient of multiple determination R^2 is 0.983076 for Eq. (4), 0.975322 for Eq. (5), and 0.970858 for Eq. (6).

6. Sensitivity analysis

The influence of the six independent variables $x_1 - x_6$ on the three dependent variables, respectively the effluent concentrations of ammonia y_{NH4}, nitrate y_{NO3}, and phosphorus y_{Ph} was investigated by Monte Carlo simulation using CRYSTAL BALL® software. CRYSTAL BALL was created as an EXCEL add-in.

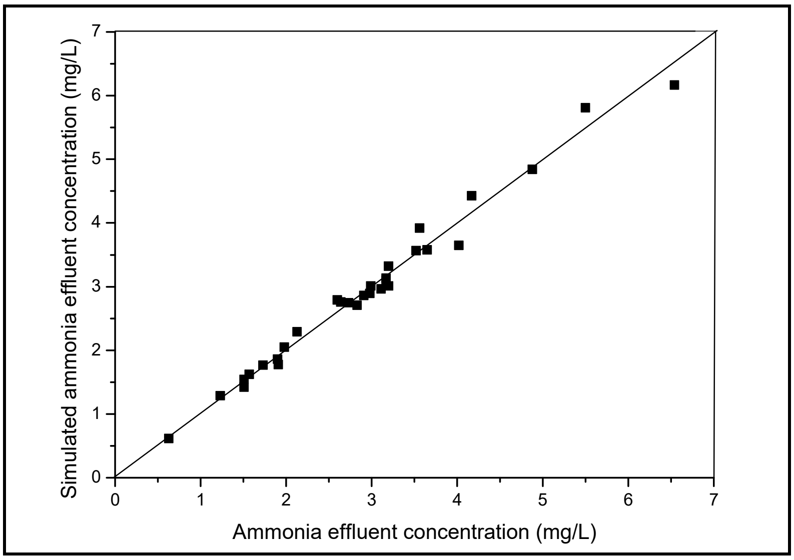

Fig. 6. Comparison of simulated and regression values of ammonia effluent concentrations

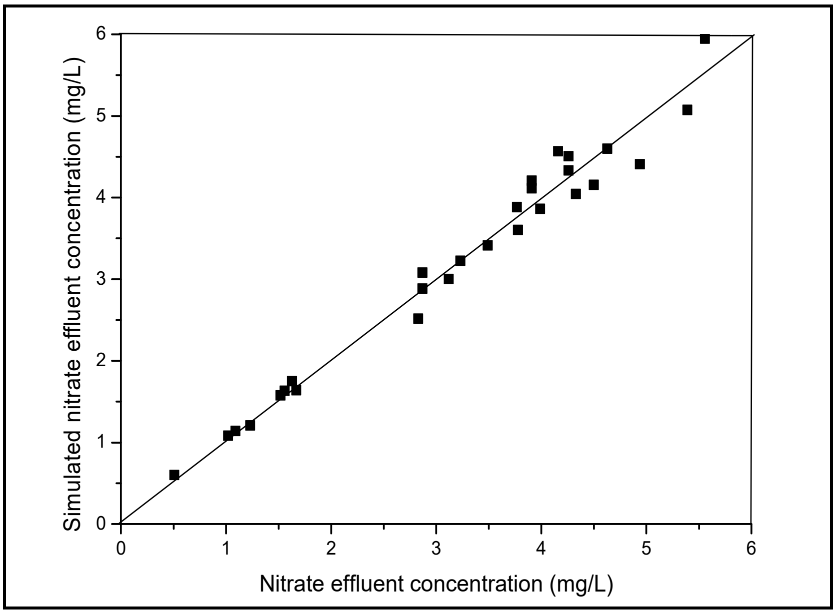

Fig. 7. Comparison of simulated and regression values of nitrate effluent concentrations

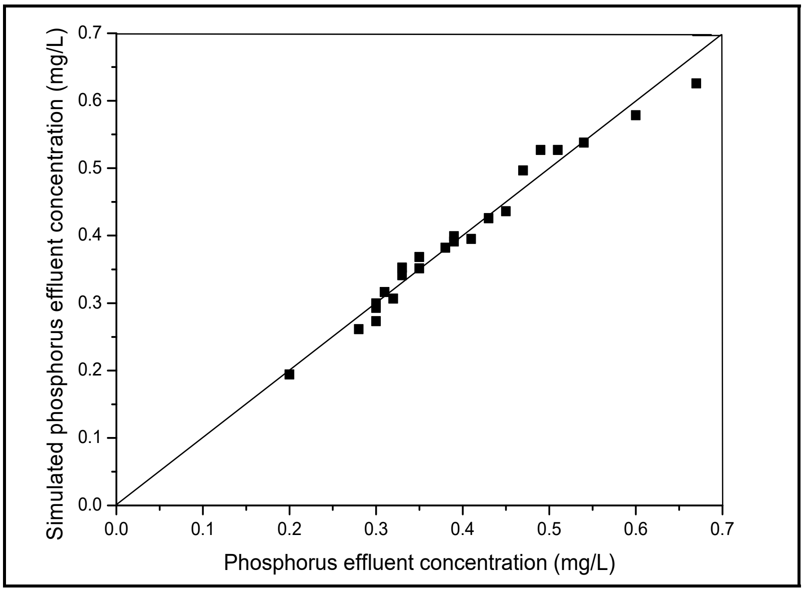

Fig. 8. Comparison of simulated and regression values of phosphorus effluent concentrations

CRYSTAL BALL enhances EXCEL by describing the uncertainty for any cell, and allowing to calculate the effect of uncertainty on the variables of interest. CRYSTAL BALL uses Monte Carlo simulation to dynamically produce alternative scenarios in the spreadsheet model. The detailed mode of using CRYSTAL BALL for sensitivity analysis was presented by Woinaroschy (2008). The independent variables $x_1 - x_6$ were selected as "assumptions" with uniform distribution between minimum and maximum values.

The selected "forecast" is affected by assumption, on the base of corresponding Eqs. (4-6). The total number of simulations was set to 1,000,000. When CRYSTAL BALL runs a simulation, it stores all forecast values. During a simulation, CRYSTAL BALL ranks the assumptions according to their importance to each forecast and indicate which assumptions are the most important or least important in the model. At the end of simulation, CRYSTAL BALL generates many reports and charts. For the present application the interest is concentrated to the sensitivity charts. These give the percentage contributions to variance (Figs. 9-11).

Important weights of contributions to variance for all three pollutants effluent concentrations are for reaction time: -40% for ammonia effluent concentration, -30.7% for nitrate effluent concentration, and -47.3% for phosphorus effluent concentration. The negative values of these contributions indicate correctly that when reaction time increases the effluent concentrations decrease.

Another correct result refers to the weights of input pollutants concentrations: the weight of ammonia input concentration is 57.9% for ammonia effluent concentration, the weight of nitrate input concentration is 68.3% for nitrate effluent concentration, and the weight of phosphorus input concentration is 51.2% for phosphorus effluent concentration. The weights of the other input parameters are not significant. These quantitative results are important for correct process operating: when the effluent concentration of a pollutant increase over the accepted value, the corresponding value of input concentration must be decreased by dilution with fresh water, and/or by increasing the reaction time. The simulation of these actions can be made with Eqs. (4-6).

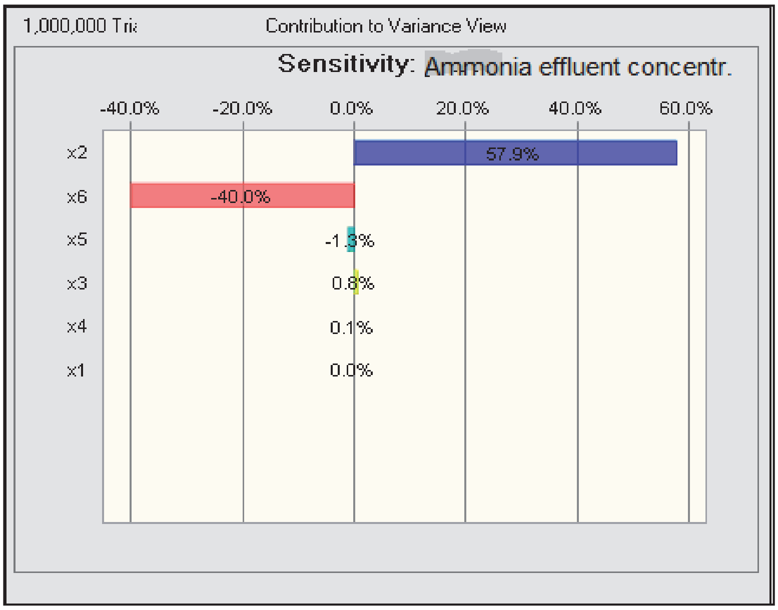

Fig. 9. Sensitivity chart for ammonia effluent concentration

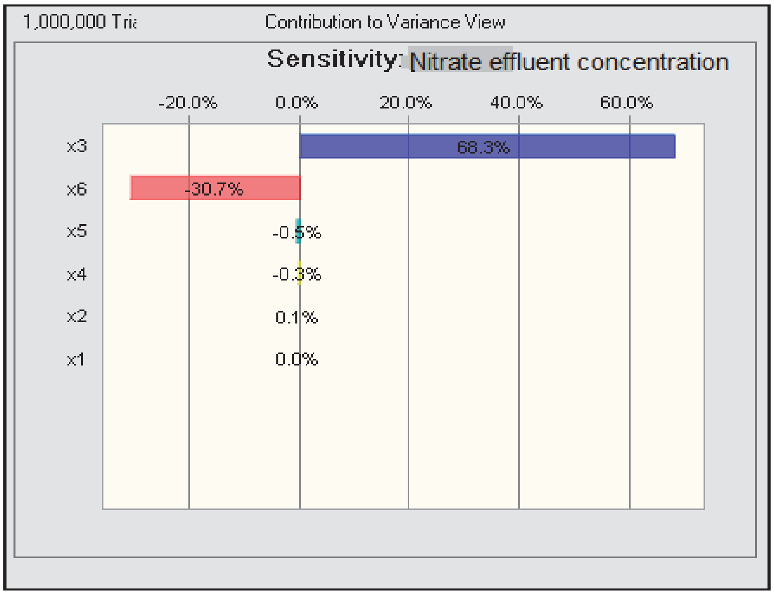

Fig. 10. Sensitivity chart for nitrate effluent concentration

6. Conclusions

The SBR process is a simplified one because all the unitary processes are carried out in a single tank. SBR technology has the advantage of being more flexible than conventional sludge processes in terms of matching reaction times with the concentration and degree of treatment required for a particular wastewater. An important advantage of using SBRs is the high effluent quality, so that major pollutants, ammonium and phosphates are reduced by 96%, and respectively by 88%.

The following parameters have been monitored: ammonia, nitrate, and phosphorus effluent concentrations. The results obtained from the simulations are in line with the practical results determined in the laboratory, and their values fall within the limits imposed by the authorities.

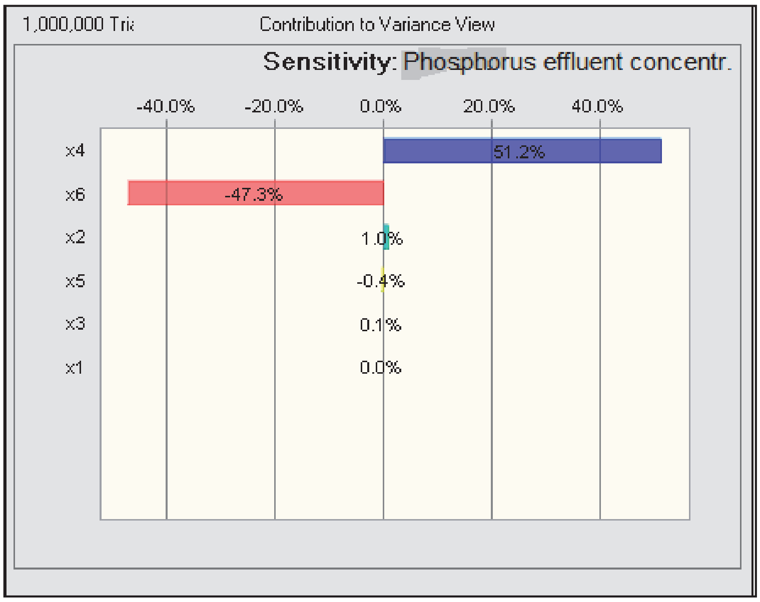

Fig. 11. Sensitivity chart for phosphorus effluent concentration

The novelty of this paper consists in:

- obtaining a new regression model using the SBR simulation with STOAT 5.0 software, confronted with the process data collected on-line;
- extension the initial database by random generation of 100 sets of process data, and the values of effluent pollutants concentrations for each set were calculated, using the simulator STOAT 5.0;
- an original two-step regression procedure;
- the use of the equations obtained after the second stage of the two-step regression procedure in the framework of a sensitivity analysis by Monte Carlo simulation and establishing a guide for correct operation of the sewage treatment plant. According to this guide, when the effluent pollutant concentration increases over the accepted value, the corresponding value of input concentration must be decreased by dilution with fresh water, and/or by increasing the reaction time.

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