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THE EFFECTS OF OPTIMIZING A SIMULATED WASTEWATER TREATMENT PLANT ON EFFLUENT QUALITY

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Abstract

Wastewater treatment plants with activated sludge behave like a filter to protect the aquatic environment and also the health of those who use and consume the water. These treatment plants are used to remove nutrients from wastewater, such as nitrogen, that can have a great impact on the evolution of the aquatic ecosystem if we consider the eutrophication process that is intensified worldwide due to agriculture and other industrial activities. In this study, a wastewater treatment plant model called Benchmark Simulation Model No.2 (BSM2) was used to regulate ammonium and nitrate concentrations by implementing a control strategy. The strategy optimization was performed by applying the relaxation method. The reference data considered are the results of the simulation with the BSM2's base control strategy in a closed loop. Also, the data obtained in the first attempt of optimizing the treatment plant were considered. This study aims to identify if the optimization of the simulated wastewater treatment plant can improve the effluent quality thus reducing the risk of aquatic environment pollution with nutrients.

Key words: *aquatic environment, effluent, simulation, optimization, wastewater.*

INTRODUCTION

Water is essential; without it, our planet won't meet the necessary conditions to support and maintain life.

Even if our planet is rich in water, only a small portion of it is freshwater. About 70% of Earth's surface is covered in water, representing approximately 1386 million of km^3 of water. From this total amount, freshwater represents just 2.5%. If we consider the availability of fresh water to humans and other creatures, the percentage gets even lower. Almost 70% of the total amount of freshwater is present in form of glaciers and snow, and another part is found underground, making it hard to reach. Thereby, readily accessible freshwater represents just 0.26% of the total amount of fresh water, and it is found under forms of surface water (lakes, rivers, streams, wetlands, swamps, etc) (Baker, B.H., Aldridge, C.A., & Omer, 2016; Shiklomanov, 1998).

The qualitative and quantitative aspects of water can be considered indices of prosperity. Many biological cycles and processes, present in the aquatic ecosystems, can be perturbed if the water quality is affected by pollution. Likewise, the ecosystem can suffer or even disappear in time if the quantity of water is not sufficient to cover the needs of the inhabitants. These aspects can also be indices of human life quality. Good quality freshwater sources can sustain food production and other industrial activities without extra costs spent on water treatment. On the other side of the coin, if the wastewater resulting from such processes is not treated it can produce in time a shortage in usable freshwater due to pollution.

Statistically, 80% of the total amount of wastewater is discharged without any treatment directly into oceans, seas, lakes, and rivers.

Romania's river basin, presented in Figure 1, covers approximately 76% of the territory's surface.

Poorly developed countries have the disadvantage of lack of infrastructure or modern technology, meaning that they are unable to treat wastewater efficiently. Countries that are found in this situation can treat around 38% of the total generated wastewater. On the other hand, heavily developed countries, are aware of the economic importance of the quality of water, and with the proper infrastructure, they can treat about 70% of their wastewater (Max Roser, 2021; UNESCO, 2017; *Water Scarcity |Knowledge for Policy*, n.d.)

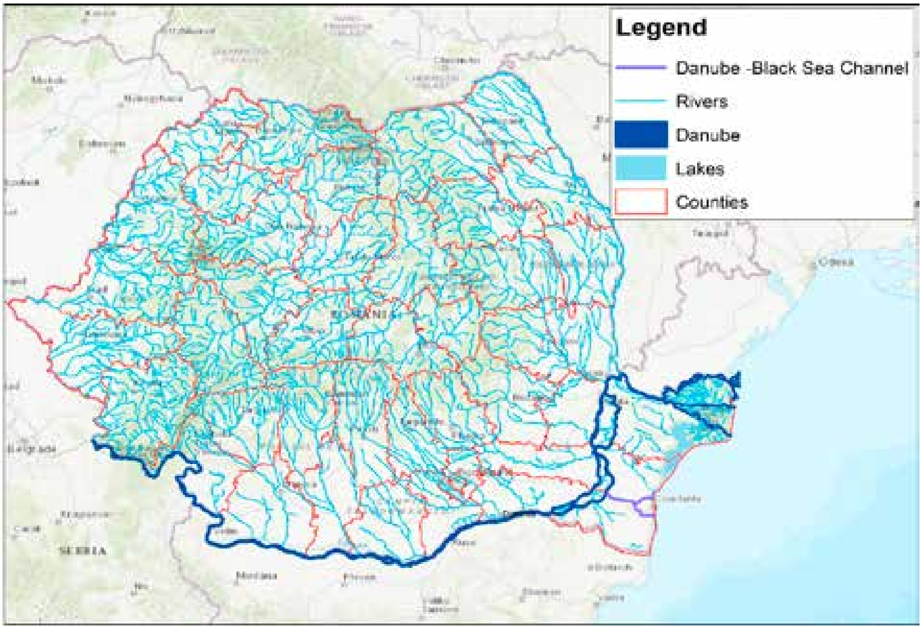


Figure 1. Romania's hydrological basin

Aquatic ecosystems are very vulnerable in case of pollution, many creatures that are part of these ecosystems are sensitive to changes in physicochemical properties of water such as temperature, total dissolved solids, turbidity, pH, alkalinity, dissolved oxygen (DO), biological oxygen demand (BOD_5), chemical oxygen demand (COD), etc. (Rosette et al., 2020). These parameters are also used to monitor the quality of a WWTP's (Wastewater Treatment Plant) effluent (Sastry et al., 2013).

The intense use of phosphorus and nitrogen-based fertilizers in agriculture represents a real ecological concern for aquatic ecosystems. Many other sources of these nutrients are available, but their combined effect can lead to the appearance of eutrophication phenomena, known also as an algal bloom. The problem with eutrophication is that it affects both, salt water and fresh water ecosystems (Wilkinson, 2017).

The effects of eutrophication on aquatic ecosystems are devastating. Oxygen depletion and accelerated growth of algae can cause a gradual decline in the biodiversity of the aquatic ecosystem (Dorgham, 2014).

A solution to this global issue is the use of WWTPs with activated sludge (Ardern & Lockett, 1914). The nutrients present in wastewater in high concentrations are removed by specific processes such as nitrification and denitrification, which help in reducing the amount of nitrate in water (Elmerich, 2002).

WWTPs can be optimized to run at their full potential by using methods from the control engineering domain. Instead of experimenting on a pilot plant, which involves some environmental risks, the use of mathematical models with the same specifications as the considered WWTP, is more reliable.

There are many benefits of using these types of mathematical models, for example, different control strategies can be applied and tested at low costs, compared with the use of some expensive equipment on a pilot plant.

BSM2 (Benchmark Simulation Model NO. 2), developed by the International Water Association (IWA), was chosen to be used in this study to perform the simulations and the evaluation of the plant performance. This paper aims to observe the effects of fine-tuning during the optimization process of an applied control strategy to the simulated WWTP. The total optimization score of the plant might vary depending on the EQI (Effluent Quality Index) and OCI (Overall Cost Index) variation caused by different input values of the control variables. The main objective is to identify if the EQI index shows any signs of improvement during the fine-tune compared to the default output values of BSM2 in a closed loop. A lower EQI score is better and it indicates that the effluent quality has improved.

MATERIALS AND METHODS

The BSM2 model, presented in Figure 2, was used in this study to simulate the WWTP. The model can evaluate the ecological and economical performances of the WWTP by analyzing the data obtained after each simulation.

The BSM2 model can simulate 2 stages of treatment that are present in a regular WWTP with activated sludge. The first stage, the wastewater treatment, is done by specific units: primary clarifier, biological reactor, and secondary clarifier. The first unit in which the influent enters is the primary clarifier, where water is separated for the first time from the sludge. The total tank volume of the primary clarifier is 900 m^3 (Alex et al., 2008).

The second, and the most important unit in the wastewater treatment stage, is the biological reactor. This unit is separated into 5 divisions, where, divisions 1 and 2 are under an anoxic regime, where the denitrification takes place. Divisions 3, 4, and 5 are under an aerated regime, where the nitrification process takes place. The total volume of the simulated biological reactor is 12000 m^3 (Alex et al., 2018; Nopens et al., 2010).

The secondary clarifier has a total volume of 6000 m^3, being modeled as a unit with 10 levels, where each level is 0.4 m tall. The purpose of the secondary clarifier is to separate the sludge from the treated water. The treated water found at the 10'th layer of the secondary clarifier is removed from the installation, representing the effluent. The secondary clarifier is considered biologically and chemically inert (Alex et al., 2018).

The second stage, the sludge treatment, is conducted by different units: thickener, one anaerobic digester, and the dewatering installation.

The most important unit in the sludge treatment stage is the anaerobic digestor, an installation where methane gas is obtained in the process of sludge reduction, the produced biogas is further used for the energetical autonomy of the plant.

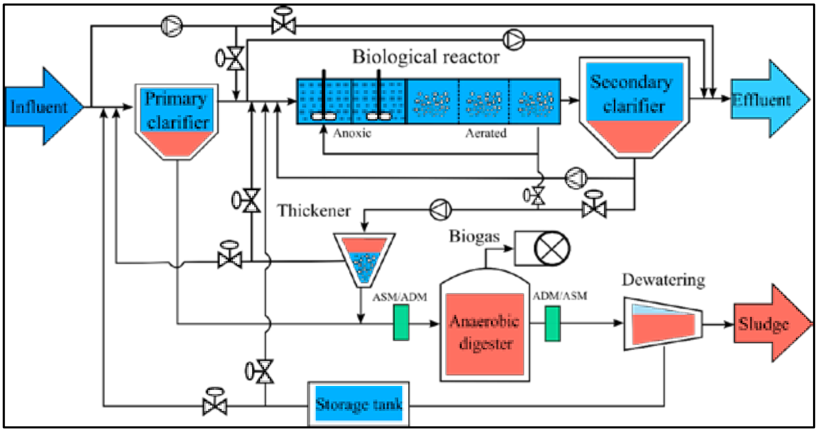


Figure 2. BSM2 plant layout (adapted after Alex et al., 2018; Nopens et al., 2010)

BSM2 imports an external file that contains the data for the influent components for 609 days. BSM2 simulates 609 days in which the WWTP operates, the first 245 days represent the stabilization period, followed by 364 days of observation (Alex et al., 2018).

The ecological performance of the WWTP is defined by the EQI expressed as kg pollution unit/day. This index is calculated during the observation period as an average value of the effluent loads of compounds that have a great impact on the aquatic ecosystems.

The EQI is represented in the work of Alex et al., 2018, with the formula:

$$EQI = \frac{1}{t_{obs} \cdot 1000} = \int_{t=245\ dayss}^{t=609\ dayss} \begin{pmatrix} B_{TSS} \cdot TSS_e(t) + B_{COD} \cdot COD_e(t) + B_{NKj} \cdot S_{NKj,e}(t) \\ +B_{NO} \cdot S_{NO,e}(t) + B_{BOD5} \cdot BOD_e(t) \end{pmatrix} Q_e\,(t) \cdot dt \qquad (1)$$

where: TSS – total suspended solids, COD – chemical oxygen demand, NKj – Kjeldahl nitrogen concentration, NO – nitrite and nitrate concentration, BOD_5 represents the biochemical oxygen demand.

The OCI represents the economic performance of the simulated WWTP during the observation period. The OCI index is presented in the work of (Alex et all…cite) on the technical description of BSM2, with the following formula (Alex et al., 2018):

$$OCI=AE+PE+3 \cdot SP+3 \cdot EC+ME-6 \cdot MET_{prod}+HE_{net} \qquad (2)$$

where: AE - aeration energy, PE - pumping energy, SP - sludge production, EC - external carbon consumption, ME - mixing energy, MET_{prod} - biogas, HE_{net} - heating energy.

This paper is a continuation of the investigations regarding the use of the control strategy α_1, presented for the first time in Roșu et al., 2021, where the first and the second iterations were performed. The third and the fourth iterations were performed and evaluated in the content of this paper. The α_1 control strategy was used in this study to compare its results obtained during the fine-tune with the default BSM2 performance and to observe the impact on the effluent quality. The applied strategy α1 is proposed to regulate the concentrations of NO_3^-, and NH_4^+ by carbon insertion in the second division of the biological reactor, and, respectively, by oxygen addition in the fifth division of the same unit.

The third iteration was performed using the results obtained during the second iteration presented in (Roșu et al., 2021). The values for the control variables used in the third iteration were chosen using a 0.25 step in the range of the previously obtained values, 1.3 g N/m^3 for $S_{NO,div2}$ (NO_3^- control) and 0.7 g N/m^3 for $S_{NH,div5}$ (NH_4^+ control).

The fourth iteration was performed by using the data from the third iteration, this time for the $S_{NO,div2}$ the step was 0.2, and for $S_{NH,div5}$ was kept at 0.25, this was done to fine-tune the variables in such a way that the range will become narrower.

BMS2 uses a default control strategy for the closed-loop simulation to sustain the DO concentrations in the 5'th division of the biological reactor at a preset of 2 g (-COD)/m^3. The process is done by controlling the actuator model representing the oxygen transfer coefficient (K_La_4) in the 4'th division of the biological reactor in such a way that the following requirements are met: $K_La_3 = K_La_4$; $K_La_5 = K_La_4/2$. Furthermore, the default strategy also involves the addition of external carbon in the first anoxic division of the biological reactor, at a rate of 2 m^3/day, to increase the denitrification potential (Alex et al., 2018).

The results obtained with the default strategy can be used as a benchmark for other user-made control strategies. In this paper, the results of the BSM2's default strategy simulation are considered only as a secondary reference. The main reference used for comparison is the data obtained during the first iteration.

BSM2 uses the following concentration limit values for 5 essential effluent quality parameters: total nitrogen (N_{tot}) < 18 g N/m^3, COD_{tot} < 100 g COD/m^3, ammonia and ammonium nitrogen (S_{NH}) < 4 g N/m^3, TSS < 30 g SS/m^3, BOD_5 < 10 g BOD/m^3. The considered parameters are calculated during the evaluation period of the simulated WWTP, all the values above these limits contribute to an increased EQI final score.

To simplify the results, an optimization criterion (O_c) was used as in Luca et al., 2017:

$$O_c=\beta(EQIs+TD_{Ntot}+TD_{SNH,e})/3+(1-\beta)OCIs \qquad (3)$$

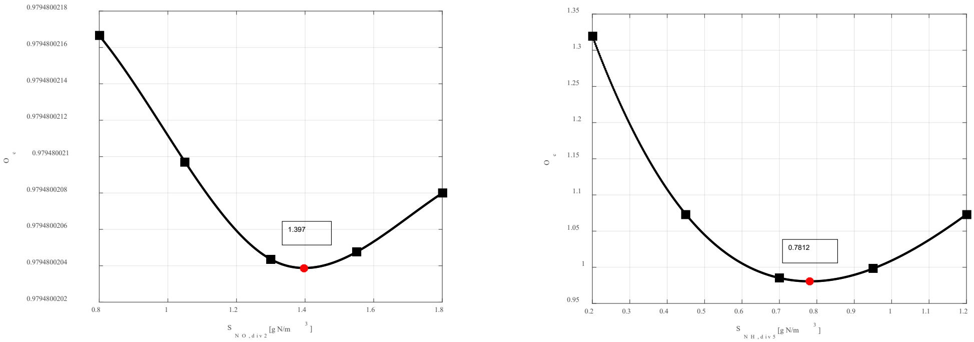
where: EQIs and OCIs represent the scaled EQI and OCI values, TD_{Ntot} and $TD_{SNH,e}$ are the scaled values of the time when the concentration limits for N_{tot} and $S_{NH,e}$ were exceeded. The β factor can have any value between 0 and 1, this factor indicates the importance of the economic and effluent quality impact. In our case, the β factor was set at the 0.5 value. The scaling factors are EQI, OCI, N_{tot}, and $S_{NH,e}$ obtained during the first iteration of α_1 strategy.

The optimization process is based on the relaxation method. The first step is to optimize independently the control variables $S_{NO,div2}$, and $S_{NH,div5}$; 5 values are attributed for each variable per iteration and are chosen around the reference value with a preferred step of 0.25 or lower. After each simulation, the interest values from the results are scaled and the optimization criterion formula is applied. The next step is to obtain the polynomial interpolation between O_c and the $S_{NO,div2}$, and $S_{NH,div5}$ values. At this point, we must identify the minimum point from the polynomial interpolation and use the identified value for the control variable as a reference set point for the next iteration. Near the end of the optimization process, a final simulation is performed, where we use both of the final optimized values for N_{tot} and $S_{NH,e}$, obtained during the individual optimization process. At this point, a final O_c value is obtained, summarizing the final score of the control strategy per iteration.

RESULTS AND DISCUSSIONS

The α_1 control strategy, described in the previous chapter, was applied and used with the BSM2.

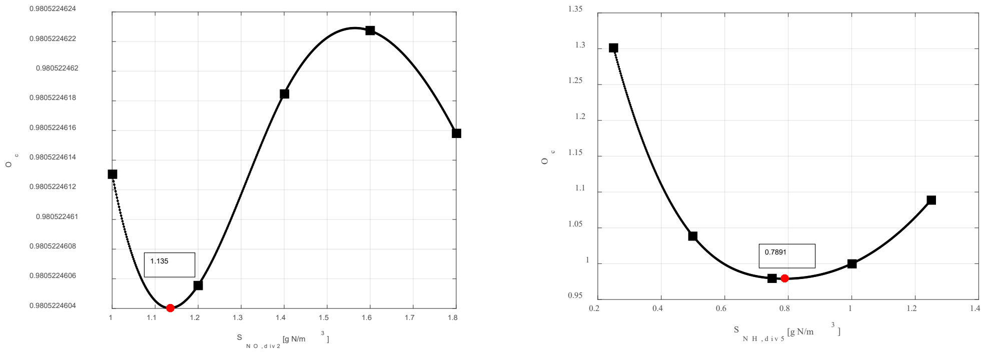
Figures 3 a) and b) represent the interpolation curve of the data obtained during the independent optimization of the control variables from the third iteration. In this stage, 10 simulations were performed to optimize $S_{NO,div2}$, and $S_{NH,div5}$. The minimum point which indicates the most optimized value for $S_{NO,div2}$ was determined at 1.397 g N/m^3. In the case of $S_{NH,div5}$ variable, the minimum point was identified at 0.781 g N/m^3. In both cases, the curve has a descending evolution from the first simulation until it reaches the minimum point, which was found in both cases between simulation no. 3 and 4.



a) *b)*

Figure 3. Optimisation process of control variables during iteration no. 3

Figures 4 a) and b) represent the interpolation curve obtained during the 4'th iteration. For $S_{NO,div2}$, the optimal value was identified between the first and the second simulation at 1.135 g N/m^3. Figure 4 b) presents the case for the $S_{NH,div5}$ control variable. The minimum point from the interpolation was identified between simulations no. 4 and 5 at a value of 0.789 g N/m^3. It is noticeable that the interpolated curve presented in Figure 4 a) has a different shape compared to the one from the third iteration and, also, did find the optimal value faster. This could be caused by the lower step used in the range of the chosen values for $S_{NO,div2}$.



a) *b)*

Figure 4. Optimisation process of control variables during iteration no. 4

A simulation with the optimal values for the control variables was performed at the end of each iteration, to test how the performance is affected when both optimized control variables are used. Figure 5 presents the final data obtained for the optimization criterion from all 4 iterations. The lowest EQI value is recorded in the 4th iteration, but this comes at a cost with an increased OCI value, being the highest recorded from all 4 iterations.

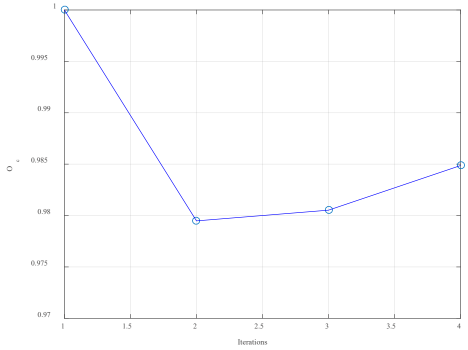


Figure 5. Final score for O$_c$ during the optimization process

Figure 6 shows a direct comparison between the EQI values obtained with the default control strategy of BSM2 (EQI$_{def}$) and the EQI obtained at the 4th iteration with α$_1$ strategy (EQ$_{\alpha1,it4}$).

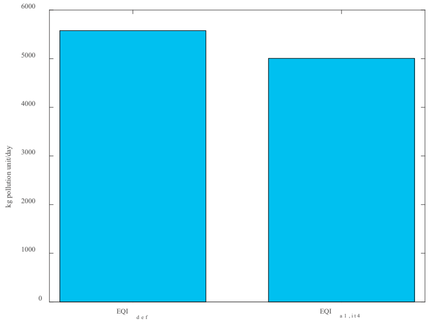


Figure 6. EQI data comparison between the default BSM2 strategy and α$_1$ strategy in the 4'th iteration

CONCLUSIONS

WWTPs play a major role in maintaining the aquatic ecosystems clean. By optimizing the performance of these installations, better water quality can be obtained. The optimization method used in this paper has proven to be useful to fine-tune user-made control strategies for the BSM2 model, which simulates a WWTP. The optimization has shown to have a good ecological impact, that being shown by the final EQI score obtained at the 4th iteration, which indicates an improved quality of the effluent. Further investigations might be needed to be done to reach the iteration at which the optimization criteria will stabilize.

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